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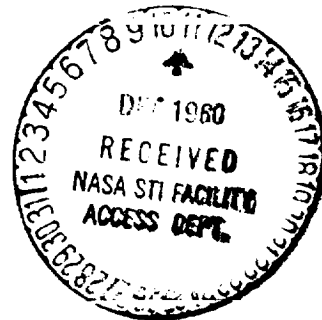
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AIRCRAFT SURFACE COATINGS STUDY

ENERGY EFFICIENT TRANSPORT PROGRAM

BOEING COMMERCIAL AIRPLANE COMPANY,
P.O. BOX 3707, SEATTLE, WA 98124

CONTRACT NAS1-14742, TASK 4.1.3
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Langley Research Center
Hampton, Virginia 23665

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FOREWORD

This document is the final report for a portion of Task 4.1—natural laminar flow (NLF), one of five tasks defined by the Statement of Work for Contract NAS1-14742. In total, Task 4.1 encompassed three significant areas of investigation: 1) aircraft surface coatings study, the subject of this report, 2) flight test of selected surface coatings, and 3) NLF airfoil analysis and trade studies. The aircraft surface coatings study was conducted during the period of August 1977 through June 1978. Mr. D. B. Middleton of the Energy Efficient Transport Project office at Langley Research Center was the NASA technical monitor.

The investigations were conducted within the Preliminary Design department of the Vice President—Engineering Organization, Boeing Commercial Airplane Company, and by Avco Systems Division as a major subcontractor. Personnel participating are listed below:

Boeing

G. W. Hanks	Program Manager
R. L. Kreitingner	Task Manager
R. P. Thierry	Materials Technology
R. H. Kimble	Economic Analysis
T. J. Kelly	Manufacturing Engineering
W. A. Blissell	Aerodynamics

Avco

K. M. Jacobs	Program Manager—Avco
J. G. Alexander	Principal Investigator
J. S. Johnson	Materials Technology

Principal measurements and calculations used during this study were in customary units.

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1.0 SUMMARY

The aircraft surface coatings study investigated the application of adhesively bonded films and liquid coatings to transport aircraft aerodynamic surfaces in order to reduce drag.

An operating environment was established, using 727 data and other current jet transport environmental design requirements, and requirements for surface coating materials were developed. An initial list of available materials was reviewed. Nine liquid coatings and 60 film/adhesive systems were selected for screening tests. Screening test results were evaluated, and nine liquid coatings and 16 film/adhesive concepts were then subjected to more rigorous advanced testing. The tests included prolonged exposure to fluids used in, and on, commercial transports, ultraviolet rays, ozone, salt atmosphere, temperature and pressure shock, peel strength and high-velocity rain impact. Three liquid coating and four film/adhesive concepts emerged as final candidates for further investigation.

Test results showed that elastomeric polyurethane liquid coatings were superior to any of the film/adhesive concepts tested for resistance to rain erosion. Further, they were relatively easy to apply and presented a smooth surface. The liquid coating concepts selected as final candidates were:

CAAPCO B-274
Chemglaze M313
Astrocoat

Four film/adhesive concepts were selected as final candidates for application in low-erosion areas:

FILM	ADHESIVE
Tradlon (polyparabanic acid)	PR 1422 (polysulfide)
Kapton (polyimide)	PR 1422 (polysulfide)
UHMW (polyolefin)	Adhesive-backed
Kynar 500 (polyvinylidene fluoride)	Adhesive 80 (fluorocarbon)

Results of environmental and rain erosion testing of these seven concepts are summarized in table 1.

The polyurethane liquid coatings showed satisfactory characteristics in environmental testing, except that they were susceptible to deterioration after extensive exposure to hydraulic fluid of the type used in commercial transports. The unresolved problem with film/adhesive systems is that there is currently no conceived method of application to large curved surfaces that is not prohibitively expensive. In addition, research should be continued into adhesives to be used with the films, to improve bond strength.

A cost/benefits analysis was performed, based on study results supported by Contractor experience in applying paints, films, and coatings to aircraft. It was estimated that a coating applied back to the rear spar of the 727 wing and empennage surfaces could reduce airplane drag by as much as 1.6%. This translates to an annual fuel saving of about 128.7 m³ (34,000 gal) per 727 airplane. As shown in figure 1, if only one-third of that potential drag benefit were realized, the fuel savings at \$106/m³ (40 ¢/gal) would offset the costs of coating application and maintenance.

Table 1. Summary of Test Results

	Environmental tests	Rain erosion tests (min)
Liquid coatings: CAAPCO B-274 (polyurethane) Chemglaze M313 (polyurethane) Astrocoat (MIL-C-83231)	All liquid coatings satisfactory, except dissolved after extended immersion in hydraulic fluid. Slightly affected by 30-day immersion in hot water.	402 (avg) *
		200 (avg)
		125 (avg)
Film/adhesive concepts: Tradlon/PR1422 (polyparabanic acid/polysulfide) Kapton/PR1422 (polyimide/polysulfide) UHMW Polyolefin (adhesive-backed) Kynar/Adhesive 80 (polyvinylidene fluoride/fluorocarbon)	Satisfactory, except reduced adhesion after 62-day salt spray exposure Satisfactory, except slightly affected by 30-day immersion in jet-A fuel Satisfactory, except bond failure after 30-day immersion in jet-A fuel Satisfactory, except bond failure after 30-day immersion in jet-A fuel. Also affected by 30-day immersion in hydraulic fluid	8 3 8 2

*Equivalent to nearly 6000 flight-hours in airline operation

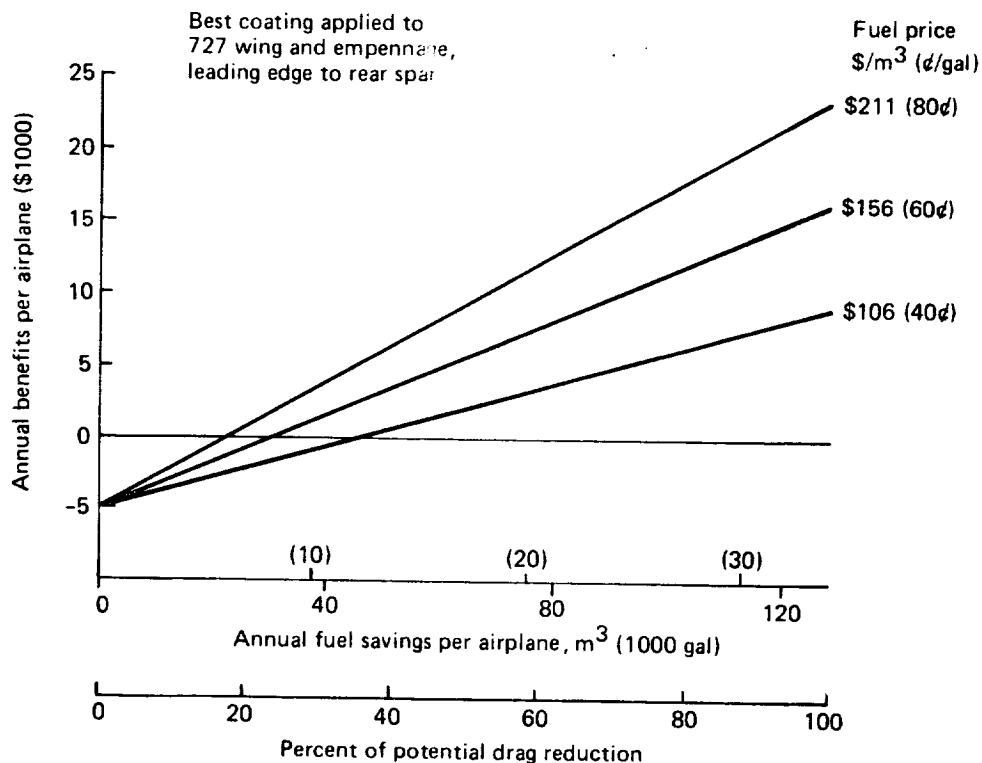


Figure 1. Potential Benefits From Surface Coating on 727-Type Airplane

At the conclusion of the study a flight service evaluation of two polyurethane liquid coatings was initiated. CAAPCO B-274 and Chemglaze M313 were applied to wing and horizontal tail leading edges of an Air Micronesia 727 by Continental Airlines. Results of this evaluation will be reported separately.

It is recommended that research and development be continued in three areas, with major emphasis on liquid coatings:

- Flight/wind tunnel testing to obtain drag reduction measurements
- Large-scale applications to develop procedures for application, maintenance, and repair
- Extended service evaluations in an airline environment to evaluate durability and other characteristics of coatings after prolonged exposure to environmental factors

2.0 INTRODUCTION

Background

It is estimated from reference 1 that the United States commercial airlines consumed approximately $37 \times 10^6 \text{ m}^3$ (233 million barrels) of fuel in 1977. With current jet fuel at about \$106/m³ (40 ¢/gal), fuel costs have become the largest single contributor to airline direct operating costs. As a result, the conservation of fuel is important from the standpoint of airline cost reduction as well as energy conservation. A third important consideration is the significant impact of foreign oil imports on the U.S. balance of payments.

The study of surface coatings to reduce the drag of commercial transport aircraft is one of many areas investigated by NASA and industry under the Energy Efficient Transport (EET) element of the Aircraft Energy Efficiency (ACEE) program. The overall objective of the ACEE program is to improve the energy efficiency of air transportation to conserve petroleum fuel.

Objective and Scope

The specific objective of this study was to investigate surface coating materials and application processes that would produce a net reduction in drag; have high resistance to corrosion, erosion, and peeling; and could be maintained easily. The scope of the study was limited to the investigation of "promising" materials and processes currently available. The study was structured into three major activities as shown in figure 2: requirements definition, materials and process testing, and cost/benefits analysis. Results were assessed and recommendations made as reported in this document. A flight service evaluation of two of the liquid coatings, to be conducted over an extended period, was initiated at the conclusion of the study.

The airframe industry reacted immediately to the 1973 fuel crises by recommending to the airlines revised operating and maintenance procedures (ref. 2). In the latter area, the importance of maintaining smooth faired external surfaces was emphasized, to keep airplane drag at a minimum. It was pointed out in reference 2 that the wing, empennage, forward body, and nacelle inlets were especially critical areas. The present study addresses drag reduction of the wing and empennage; however, the findings apply generally to other areas of the airplane.

The drag of lifting surfaces (excluding drag due to lift) is the sum of drag due to shape, roughness, and excrescences. A recent NASA wind tunnel test (ref. 3) of a T-33 wing section showed a drag reduction of about 12% when skin joints, hinge lines, etc. were faired and covered with a smooth thin film. This reduction was achieved with essentially a full-chord turbulent boundary layer. A current transport wing, with almost full-span high-lift devices and control surfaces, would not realize that degree of improvement because of excrescence drag from gaps and hinges associated with movable parts.

The reduction in drag from surface coatings also depends on the condition of the untreated surface, which is a function of original condition, flight-hours, airline routes flown, and airline maintenance practices. The condition varies greatly between airlines. Some airlines report severe erosion problems that, in extreme cases, affect low-speed handling characteristics. Several airlines report mild erosion problems; most report no erosion problem. The reports are subjective and

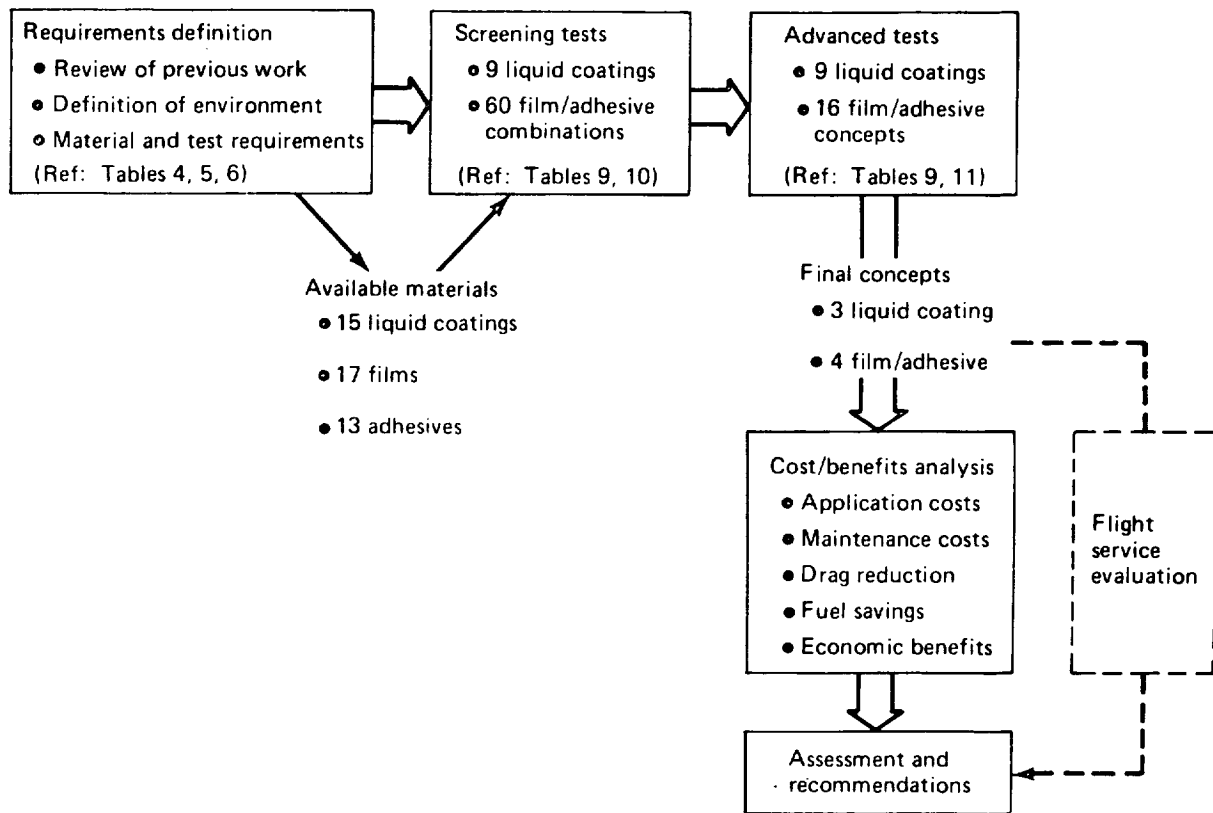


Figure 2. Study Method

qualitative in nature; therefore, no quantitative data base was available from which drag improvements could be estimated. In lieu of a data base, a severe operating environment was postulated, and study results are shown parametrically for the range of practical improvements thought to be achievable.

As the materials and process testing task progressed, it became increasingly evident that difficulties with film/adhesive systems could not be satisfactorily resolved within the scope of the study. On the other hand, some of the spray-on coating materials showed interesting potential. As a consequence, some effort was shifted from films to coatings during the latter part of the study.

Document Format

Section 4.0—Study Results, contains a discussion of the three study task activities and the results obtained. Section 5.0—Conclusions and Recommendations, contains an assessment of results and recommendations relative to the continued development of this technology. Some of the more detailed background information is included in Appendixes. Appendix A contains abstracts of previous work. Appendix B describes Contractor test procedures referenced in the document.

Appendix C contains detailed results from the material and process tests. Appendix D describes methods used in applying the materials to substrate specimens. Appendix E summarizes P-static (precipitation static) electrical characteristics testing done on selected materials.

NOTE:

Certain commercial materials are identified in this paper in order to specify adequately which materials were investigated in the research effort. In no case does such identification imply recommendation or endorsement of the product by NASA or Boeing, nor does it imply that the materials are necessarily the only ones or the best ones available for the purpose.

3.0 SYMBOLS AND ABBREVIATIONS

AFML	Air Force Materials Laboratory
AMRDL	Army Materials Research and Development Laboratory
AOG	Airplane on ground
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
b	Slope of S-log N fatigue curve
BMS	Boeing Materials Specification
CPS	Centipoise
CRES	Corrosion resistant steel
d	Drop size (mm)
FAA	Federal Aviation Administration
FOD	Foreign object damage
FTMS	Federal test method standard
keas	Equivalent air speed, knots
kn	Knots
L.E.	Leading edge
M	Mach number
mil	0.001 in
N	Number of cycles (fatigue analysis)
NADC	Naval Air Development Center
N_i	number of impacts per m^2
P	Pressure

ppm	Parts per million
P-static	Precipitation static
S_c	Effective fatigue strength in coating
S	Stress level (fatigue analysis)
USAF	United States Air Force
USN	United States Navy
UHMW	Ultrahigh molecular weight
V	Velocity
Z_c	Acoustic impedance of coating
Z_w	Acoustic impedance of droplet
δ_c	Average stress in coating
δ_u	Ultimate tensile strength of coating
λ	Wave length
ν	Poisson's Ratio

4.0 STUDY RESULTS

The analyses and testing conducted during the aircraft surface coatings study drew upon the experience and facilities of The Boeing Company and Avco Systems Division, as a major subcontractor. Boeing developed the transport operating environment and the materials test requirements, and did the cost/benefits analysis. Avco was responsible for the testing and analysis of test results; the only exception was that P-static tests were conducted by Boeing.

The task of selecting a material that was clearly superior to other materials as a coating for drag reduction proved to be more complex than was anticipated. Because of time constraints on the study, several interesting materials were not thoroughly evaluated. Those selected as final candidates cannot be recommended for transport application until further investigations have been made. As this section describes, spray-on coatings appear to be superior to films for erosion resistance, whereas films would be satisfactory for low-erosion areas if adhesion and large-scale application problems can be resolved.

The results of the Cost/Benefits Analysis (sec. 4.4) are shown parametrically. Additional data are needed, from flight/wind tunnel drag measurement tests, service life tests, and large-scale application experience to support a more rigorous evaluation of costs and benefits.

A flight service evaluation of selected final coating candidates was scheduled to begin late in the study and continue for an extended period of time. This activity is in progress, with Continental Airlines flying two polyurethane liquid coating materials on an Air Micronesia 727. Results, as they become available, will be documented separately.

The following parts of this section discuss the jet transport operating environment, the definition of requirements for coating materials, the testing of materials and processes, and the analysis of costs and benefits.

4.1 JET TRANSPORT OPERATING ENVIRONMENT

The operating environment of a medium-range subsonic jet was developed from Boeing 727 airline fleet data, and from current environmental design requirements for medium-range aircraft. The 727 fleet data were used because of the large number of airplanes (1227) in airline service, and the worldwide route systems flown by the 55 user airlines.

Table 2 summarizes 727 fleet utilization data. The 1182 airplanes for which pertinent data were available logged 8345 block hr per day, for an average of 7.06 hr per day per airplane. Although the 727 is designed for one-stop transcontinental service, its average stage length is about 852 km (460 nmi). It was postulated that the trends toward direct service will result in longer flights and fewer flights per day than historical data show, and utilization of current/future medium range transports will more closely approach their design conditions. Therefore, a typical profile of three flights per day was selected for the study, with each flight of about 1611km (870 nmi).

Figure 3 shows an altitude versus time usage profile for a 24-hr period. Elements of the profile, based on 727 performance data, are identified in the lower portion of the figure. It is of interest

Table 2. 727 Fleet Utilization

Airline designation	Airline	727-100		727-100C		727-200		Total fleet	Fleet daily utilization, hr	Daily fleet, hr
		Number airplanes	Average utilization	Number airplanes	Average utilization	Number airplanes	Average utilization			
AA	American Airlines	55	7.3	1	7.4	60	8.0	117	7.66	896.2
AC	Air Canada					14	7.0	14	7.0	98.0
AF	Air France					20	5.6	20	5.6	112.0
AH	Air Algerie					6	6.3	6	6.3	37.8
AN	Ansett Airlines	3	6.3	1	7.4	7	8.9	11	8.05	88.6
AS	Alaska Airlines	6	6.5	3	7.2			9	6.73	60.6
AT	Royal Air Maroc					7	7.2	7	7.2	50.4
AV	Avianca	8	5.4	2	5.4			10	5.4	54.0
AZ	Alitalia					7	3.3	7	3.3	23.1
BN	Braniff Airways	10	7.8	15	8.2	48	8.3	73	8.23	599.4
CI	China Airlines	2	5.0	1	6.6			3	5.53	16.6
CO	Continental Airlines	2	5.5	1	5.5	36	7.9	39	7.72	300.9
CP	CP Air	3	9.4			2	9.3	5	9.36	46.8
DA	Dan-Air Services	6	5.7					6	5.7	34.2
DF	Condor Flugdienst	5	6.1			7	6.4	12	6.28	75.3
DL	Delta Air Lines	5	7.8			83	8.1	88	8.08	711.3
DO	Dominican Airlines	1	6.3			1	8.6	2	7.45	14.9
EA	Eastern Air Lines	46	8.5	25	8.9	48	8.4	119	8.54	1016.7
HP	Hapag Lloyd	8	6.0					8	6.0	48.0
IA	Iraq Airways					3	5.5	3	5.5	16.5
IB	Iberia					29	6.1	29	6.1	176.9
IR	Iran National	4	6.4			6	6.6	10	6.52	65.2
IY	Yemen Airways			2	12.8			2	12.8	25.6
JL	Japan Air Lines	2	3.3					2	3.3	6.6
JM	Air Jamaica					4	5.6	4	5.6	22.4
JU	Jat Jugoslovenski Aerotransport					5	5.9	5	5.9	29.5
KE	Korean Air Lines	3	4.5					3	4.5	13.5
LA	Lan Chile Airlines	1	6.6	3	6.0			4	6.15	24.6
LB	Lloyd Aereo Boliviano	2	5.2	1	5.6	1	7.1	4	5.78	23.1
LH	Lufthansa German Airlines			11	7.4	19	7.0	30	7.15	214.4
LN	Libyan Arab Airlines					6	4.8	6	4.8	28.8
MX	Mexicana	7	6.1			16	7.9	23	7.35	169.1
NA	National Airlines	13	7.6			25	7.7	38	7.67	291.3
NB	Sterling Airways					3	10.3	3	10.3	30.9
NH	All Nippon Airways					23	6.5	23	6.5	149.5
NW	Northwest Orient Airlines	19	4.8	12	4.9	31	5.8	62	5.32	329.8
OA	Olympic Airways S.A.	1	5.2			6	5.8	7	5.71	40.0
PA	Pan American World Airways	11	5.0	2	5.7			13	5.11	66.4
PS	Pacific Southwest Airlines	2	5.3	2	5.0	23	6.1	27	5.96	160.9
QD	Transbrasil S. A.	1	8.3	7	7.9			8	7.95	63.6
QE	Air Micronesia			1	5.4			1	5.4	5.4
RB	Syrian Arab Airlines					3	7.3	3	7.3	21.9
RG	Varig Airlines	7	7.0	2	7.9			9	7.2	64.8
RJ	Alia-The Royal Jordanian Airlines					3	6.1	3	6.1	18.3
RW	Hughes Air West					3	4.5	3	4.5	13.5
SA	South African Airways	6	6.5	3	6.7			9	6.57	59.1
SC	Cruziero S.A.	8	7.3					8	7.3	58.4
TK	Turkish Airlines					5	6.5	5	6.5	32.5
TN	Trans-Australia Airlines	5	7.4			6	9.3	11	8.44	92.8
TP	Transportes Aereos Portugueses	4	6.3	3	6.0	2	6.4	9	6.22	56.0
TU	Tunis Air					8	6.1	8	6.1	48.8
TW	Trans World Airlines	27	6.6	8	6.8	39	7.5	74	7.10	525.1
UA	United Airlines	86	6.0	36	6.1	28	5.8	150	5.99	898.0
WA	Western Air Lines					24	8.0	24	8.0	192.0
ZB	Transair Sweden AB	2	8.2	1	8.6			3	8.33	25.0
55 Airlines Total		372		143		667		1182	7.06	8345.0
Not included*								45		
Total fleet								1227	6.9	

*Not included because: Not an airline, lack of data or very small operation

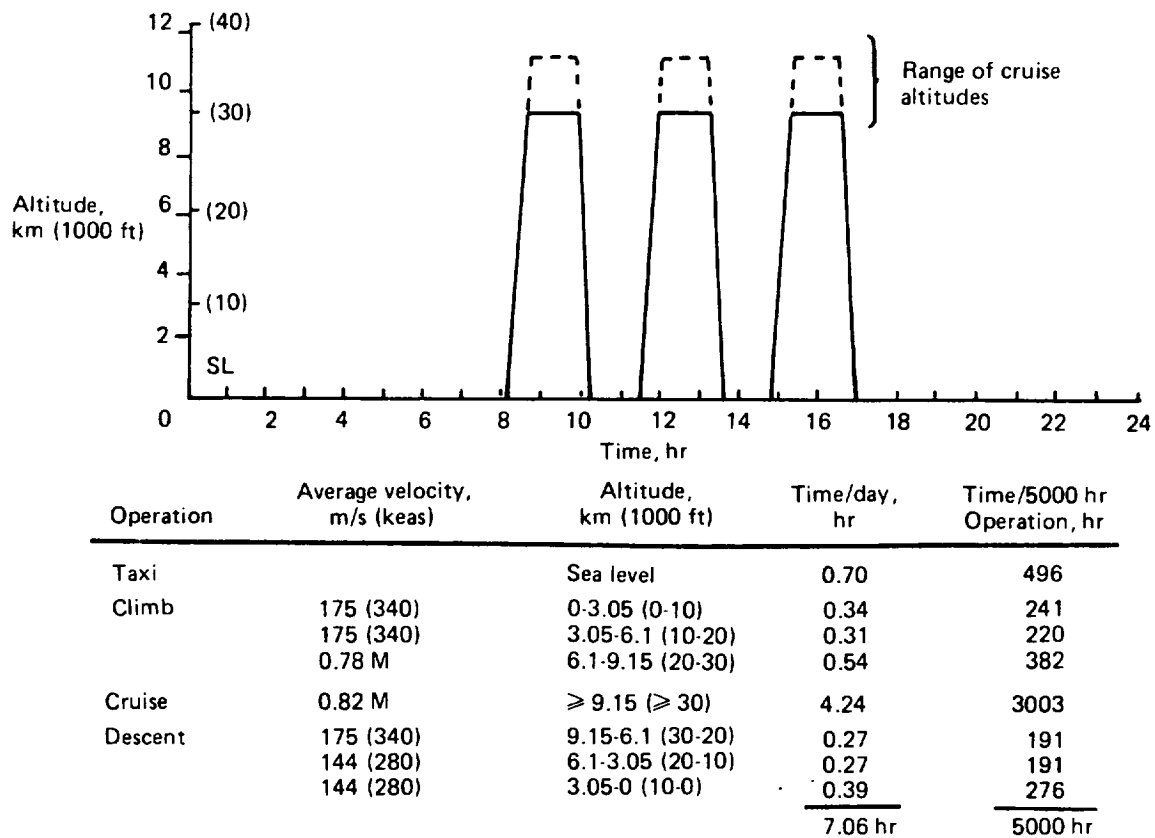


Figure 3. Typical Daily Operation – Medium Range Transport

that approximately 10% of the block operational time is spent in taxi, 30% in climb and descent, and only 60% in cruise. The greatest exposure to adverse weather is experienced at intermediate altitudes during climb and descent.

An objective of 5000 hr of operation was established as a satisfactory life for surface coatings. This equates to about 2 years in airline service. Thus, the surface coating life exposure to environmental elements includes some 3000 hr during cruise flight at, or above, 9144m (30 000 ft), 1500 hr at intermediate altitudes during climb and descent, and approximately 13 000 hr on the ground (including taxi time).

An attempt was made to relate 727 operations to actual weather exposure in their worldwide flight routes. Data were available on the number of 727 weekly departures from each of the 530 airports served by those aircraft; however, it became apparent that determining weather/climatic conditions prevalent (including seasonal variations) at each airport was far beyond the scope of the study. For reference, the distribution of 727 operations, by major world areas, is shown in table 3.

Table 3. Worldwide Distribution of 727 Operations, %

United States (48 contiguous states)	72
Central America and Caribbean	3
South America	4
Europe	10
Africa and Mediterranean	4
Pacific, Far East, and Australia	4
Canada, Alaska, and Greenland	3

Table 4 lists the environmental factors established for the study. Most of the factors were taken from current design practice requirements and objectives; some were arbitrarily established to represent severe conditions. For example, the assumption that rain would be encountered on one flight per day probably is more severe than fleet-wide operations would show, if those data were available. It was ground-ruled, on airline advice, that thunderstorms would be avoided. This is normal practice, primarily because of the turbulence passengers are exposed to, but also because of the possibility of encountering hail. Other characteristics of the rain environment were taken from reference 4.

Values for solar radiation were from reference 5. Ozone occurrence versus altitude was approximated from figure 4, which was constructed from data contained in reference 6.

4.2 REQUIREMENTS DEFINITION

Many materials available today have the potential for protecting aircraft external surfaces against erosion and corrosion, and for maintaining smooth, low-drag surfaces. The suitability of these materials depends on the environment in which they are used. A subsonic jet transport operates in a harsh environment, with extremes in temperature and pressure, high-velocity impingement of rain and dust, exposure to radiation, and exposure to a variety of fluids used in and on the airplane.

The study began with two parallel activities: a review of previous work, to determine characteristics of the various materials available for erosion protection and/or drag reduction; and the definition of surface treatment requirements in a general sense, and as translated into specific tests and test conditions. The two activities, as discussed in the following paragraphs, provided the basis for Materials and Process Testing described in section 4.3.

Table 4. Aircraft Operating Environment

Environmental factor	Ground	Flight
Temperature (°C (°F)), high low	49 (120) 54 (165)	34 (29) 73 (100)
Dynamic pressure kN/m ² (lb/ft ²)		22.8 (4.77) 193 m/s (375k) Placard sea level to 7438 m (24 400 ft), M = 0.92 above 7438 m (24 400 ft)
Ambient pressure kN/m ² (lb/in ²)	105 (15.24)	17.1 (2.48)
Humidity (%), high low	100 0	100 0
Precipitation		
Rain - Concentration	2.54 cm/hr (1 in./hr)	1000 drops/m ³ at 1524 m (5000 ft) (cloud base) 2000 drops/m ³ at 3048 m (10 000 ft) to 7620 m (25 000 ft) in cloud, no drops/m ³ above 7620 m (25 000 ft)
Drop size	1 mm	1 mm to 1524 m (5000 ft) 0.7 mm above 1524 m (5000 ft)
Density	1 g/cc	1 g/cc
NOTE: Assume a flight day through rain of the type described above. Thunderstorms will be avoided.		
Hail - Concentration Size Density	50 m ³ 0.8 cm 0.8 g/cc	11 frontal m ² at 12 192 m (40 000 ft) 5.08 cm 0.9 g/cc
Ice		FAR 25 - appendix C
Ice - Concentration Crystal size Weight		100 m ³ 5 mm 0.1 mg
Fungus	MIL STD 810B	MIL STD 810B
Salt atmosphere (ppm)	1.5	1.5
Air particles		
Blowing sand - Concentration	A few grains per foot, cross section (MIL STD 210A)	
Grain size	0.10-1.0 mm (0.15-0.3 mm predominant)	
Blowing dust - Wind (m/s (kn)) Concentration Grain size Wind (m/s (kn))	18 (35) 6 x 10 ⁻³ g/m ³ 0.0001-0.1 mm 18 (35)	
Solar radiation - W/m ² (W/ft ²)		
UV (λ 0-400 nm)	65 (6)	Total radiation increases 10% at 0 668 m (35 000 ft)
Visible (λ 400-700 nm)	549 (51)	
IR (λ 700-1400 nm)	420 (39)	
Ozone (g/m ³ x 10 ⁻⁵)		
Sea level	9144 m (30 000 ft)	6.0
10 668 m (35 000 ft)		12.1
12 192 m (40 000 ft)	6	16.4
Atmospheric electricity		
Lightning		
Current (A)		One strike/year
Megavolts		50 000
Protection		100
P-Static		See FAA Advisory Circular AC20-53 6 mA, 10% of time below 30 000 ft
Wind		
Steady	22 m/s (43 kn)	
Gusts	33 m/s (65 kn)	
Surface coating life (objective)		5000 flight hours (2 years operation)
Liquids		
Fuels	ASTM D1655	
Hydraulic fluid	BMS 3-11	
Engine oil	MIL L 23699	
Lubrication oil	MIL-L-7808	
Flap track grease	MIL C 16173	
Cleaning solutions	Greater Mountain Chemicals, BMS 3-2 528 B WADPOL, Jet Glo Number 2	
Deicing fluids	MIL A 8243, hot water	

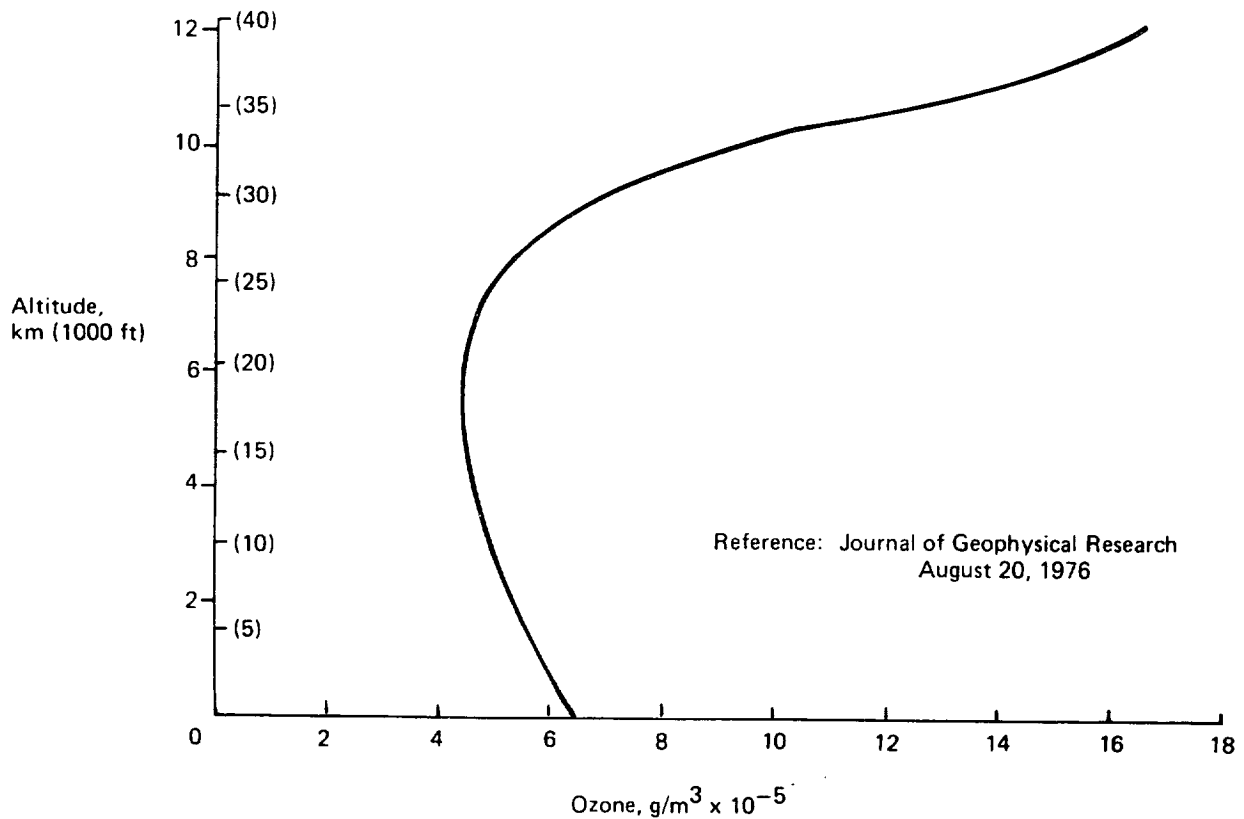


Figure 4. Ozone-Altitude Profile

4.2.1 Review of Previous Work

A review was made of previous surface coating work conducted at Boeing, Avco, AFML, NASA, and other companies and institutions to determine the availability of coating materials and processes for rain erosion protection and aerodynamic drag reduction. Abstracts of reviewed data are included as appendix A. Pertinent reports of coating and film materials are summarized in table 5. Results of previous work indicated that coating materials were superior to films in areas of high erosion exposure, such as wing and empennage leading edges. In areas where the exposure to direct impact from rain and dust particles was low, adhesively bonded films appeared to be satisfactory. Also, films are better in masking or reducing minor excrescences in the substrate to which they are applied. Based on these observations, it was decided that primary consideration would be given to coating candidates for erosion protection, and to film candidates for drag reduction in nonerosion areas.

Table 5. Summary of Previous Work

Material	Tested by	Summary
Astrocoat, Kynar 500 and Polyurethane tape	The Boeing Company 1*	Astrocoat polyurethane elastomeric coating withstood 2400 flight service hours in locations with a high frequency of rain. Polyurethane and Kynar 500 tapes peeled off.
Astrocoat	USAF-AFML 7 8 15	Black Astrocoat (MIL-C-83231) withstood up to 160 minutes in whirling arm rain erosion test at 500 mph and 1 in/hr simulated rain fall. White Astrocoat (MIL-C-83445) withstood up to 80 minutes.
Polyurethane elastomeric coatings	University of Dayton 17	Slow moisture curing systems had better rain erosion resistance than systems cured by adding additional component. Polyurethane coating systems employing a top coat 35 to 40 Shore units harder than bottom coat outperformed a single layer of either system.
Polyurethane elastomeric coatings	USAF-AFML 25	Using these coatings on large military aircraft leading edges would result in an estimated saving of \$2,000,000 per year.
Polyurethane enamels	E-Systems Incorporated 13	In rain erosion tests polyurethane enamel less than 0.051 mm (2 mils) thick in areas closer to leading edge than 20% chord failed test.
Fluoroelastomer coatings	USAF-AFML 8 15	Resistance to rain erosion in AFML 500 mph rain erosion whirling arm test was about 75% of the life of polyurethane elastomer. Fluoroelastomers will resist 260°C (500°F) as compared to 149°C (300°F) for Astrocoat.
Silicone	The Boeing Company 2	Dow Corning 92-009 silicone withstood 2500 flight service hours applied to an engine nose cowling.
Silicone	USAF-AFML	Silicone coatings survived only a few minutes (6-10) in whirling arm rain erosion tests at 500 mph and 1 in/hr simulated rainfall.
Alkyd silicone corrosion preventive compound	USN-NADC 18	Amlguard, a silicone-alkyd coating with inhibitors, was recommended by the Navy for touch-up of damaged areas. Reportedly used to protect leading edge of wing and tail of F-14. Service exposure conditions unknown.
Corogard (aluminum-filled thiokol) Polyurethane enamel	The Boeing Company 26	Equivalent sand grain roughness heights, K_s , of Corogard coating system over aluminum was $K_s = 0.0015$ to 0.0030 . Roughness of polyurethane coating system over aluminum was $K_s = 0$. Corogard roughness varied with painter technique.
Nickel	USAF-AFML 7	Electroplated nickel withstood one hour in 500 mph at 1 in/hr whirling arm rain erosion test.
Kapton	NASA 5	5-mil Kapton film reduced drag on model wing in wind tunnel test.
Ultra high molecular weight polyethylene (Dunlop) and adhesive-backed polyurethane (Dunlop)	USA-AMRDL 14	Polyurethane was superior to ultra high molecular weight polyethylene in a rain and sand erosion test and was selected for rotor blades.

*Numbered abstracts are contained in appendix A.

4.2.2 Surface Coating Requirements

The various aspects of the jet transport operating environment, as defined in section 4.1, were translated into general requirements for materials applied to aircraft surfaces for drag reduction. These general requirements were then expanded into specific test requirements by which the suitability of the materials could be measured. The tests were based on government and industry standards, and in each case, identified target performance values for the test material. Two types of tests were designed; those by which the original large list of candidate materials could be screened, and more rigorous advanced tests to which the best materials from the screening tests were subjected.

General Requirements

It was determined from the operating environment definition that films or coatings used for surface treatment must possess the general characteristics listed below:

- Withstand natural, operating, and fluid environments as defined in section 4.1
- Provide protection against rain erosion of leading edges
- Provide corrosion protection equal to, or better than, coating systems currently being used
- Have adequate adhesion as applied, and after exposure to fluids
- Present and retain a surface smoothness equal to, or better than, best current production standards
- Be easily maintained or restored to original condition

Test Requirements

Requirements and procedures were developed for initial screening tests of candidate coatings and film/adhesive systems. These tests are defined in tables 6 and 7. Materials that showed promise from the screening tests were subjected to additional, more rigorous, advanced tests as described in table 8. Both series of tests were based on American Society for Testing and Materials (ASTM), military, Boeing, and other industry standard test procedures. Performance requirements or goals are included with each procedure. Specific Boeing test procedures are included as appendix B.

Table 6. Screening Tests – Liquid Coatings

Test	Procedure	Target requirement	Test applicable to
1.1 Application life	Conduct tests 1.2 through 1.8 at the end of the application life as specified by the vendor.	Minimum 4 hr. Coating material will meet the requirements of 1.2 through 1.8 at the end of the designated life.	All liquid materials
1.2 Condition in container	FTMS 141, Method 3011	The material, both as individual and as mixed components, shall show no caking and shall be free of skins, livering, gelled particles, and contamination when viewed on the glass plate.	All liquid materials
1.3 Drying time	FTMS 141, Method 4061 Dust free Tack free Dry through Final cure	No requirement. Record for identification of product. 7 days maximum.	All liquid materials
1.4 Nonvolatile content	FTMS 141, Method 4041 or 4045	No requirement. Record for identification of product.	All liquid materials
1.5 Viscosity	FTMS 141, Method 4281, 4287 or 4282 (Ford or Zahn cups)	No requirement. Record for identification of product.	All liquid materials
1.6 Weight per gallon	FTMS 141, Method 4184	No requirement. Record for identification of product.	All liquid materials
1.7 Spraying properties	FTMS 141, Method 4331	The material, thinned as recommended by the supplier and applied at a distance of 8 to 10 in. from the panel, will have good leveling characteristics and will show no wrinkling, sagging, bubbling, streaking, solvent popping, or other irregularities.	All liquid materials
1.8 Dry adhesion	FTMS 141, Method 6301	(1) There shall be no cracking, flaking or adhesion failure between the primer and the enamel. (2) There shall be no adhesion failure between the primer and the substrate.	All materials
1.9 Wet adhesion	Repeat 1.8 after 7 days immersion in distilled water at room temperature.	Same as 1.8 above.	All materials
1.10 Flexibility	FTMS 141, Method 6222 Inspect for cracks and conduct dry adhesion test without scribing.	No cracking or loss of adhesion beyond 1/2 in. from 1/8 in. diameter end of conical mandrel. Fixed diameter mandrels may be used.	All materials
1.11 Pencil hardness	Measure pencil hardness per BMS 10-79, Procedure 7.2.5 (appendix B)	No requirement. Record results.	All materials
1.12 Fluid resistance	FTMS 141, Method 6011 (a) Test fluid TT-S-735, Type VII, room temperature 6 hr. (b) Monsanto standard density aviation hydraulic test fluid-low density (applicable wing area candidates only), room temperature 7 days.	(a) and (b) show no blistering, wrinkling, or other visible defects except slight discoloration. Measure pencil hardness and compare to dry pencil hardness.	(a) All materials (b) Nonerosion area materials
1.13 Peel strength	MIL-C-83231 or ASTM D903	10 lb/in. minimum goal. Record actual strength.	Polyurethane and other rubber-like materials.
1.14 Rain erosion	500 mph in 1 in./hr 2 mm diameter simulated rainfall	Record time to failure (penetration), penetration rate, and penetration density. Run until failure.	Erosion area materials
1.15 Smoothness	Measure surface finish before, after, and at interval(s) during test using recording profilometer, microscopically using visual standards, or equivalent.	No requirement. Results to be evaluated to rank coatings and compared with follow-on test data.	Erosion area materials

Table 7. Screening Tests — Film Candidates

Test	Procedure	Target requirement	Test applicable to
1.16 Tear strength	Test per ASTM D624 using Die B and a jaw separation rate of 20 in./min.	Minimum allowable tear strength = 90 lb/in. width.	Erosion area films
1.17 Adhesion	Bond films to 2024-T3 aluminum panels in accordance with ASTM D903 using a candidate adhesive. Test for adhesion. Test a minimum of two candidate adhesives per film.	Minimum peel strength = 10 lb/in. width minimum or film will tear off at substrate.	Nonerosion area films and adhesives
1.18 Heat aging	Prepare specimens for adhesion test per ASTM D903, age 168 hr minimum at 160°F ($\pm 5^\circ$), then peel. Test a minimum of two candidate adhesives per film.	No shrinkage or delamination. Peel strength = 10 lb/in. width minimum, or film will tear off at substrate.	Nonerosion area films and adhesives
1.19 Light stability	----Deleted----		
1.20 Moisture resistance	Prepare specimens for adhesion test per ASTM D903, then immerse them in distilled water at 72°F ($\pm 3^\circ$) for 24 hr minimum. Test a minimum of two candidate adhesives per film.	Peel strength = 10 lb/in. width minimum or film will tear off at substrate.	All films and adhesives.
1.21 Fluid resistance	Prepare test panels per ASTM D903. Immerse test films and panels in the following test solutions per ASTM D471: a) TT-S-735, Type VII for 6 hr b) Monsanto Standard Density Aviation Hydraulic Test Fluid for 168 hr.	Film tests — 15% maximum change in hardness, tensile ultimate elongation, and tear strengths. Maximum change in volume = $\frac{+6}{-15}$ % Adhesion to panels — peel strength must be 10 lb/in. width minimum or film will tear off at substrate.	a) All films b) Nonerosion area films
1.22 Rain erosion smoothness	Per 1.14 and 1.15	Per 1.14 and 1.15	Erosion area films
1.23 Shrinkage	Accurately measure 6-in. by 6-in. specimens, place in 270°F ($\pm 5^\circ$) air circulating oven and hold at temperature for 10 min. Remove, cool, and remeasure.	Allowable shrinkage = 5% Allowable deviation between batches of material = 2%	Erosion area films
1.24 Hardness	ASTM D2240, Shore A before and after heat aging per ASTM D573. ASTM D2197, Method A	As is: 60 \pm 5 After aging: 60 $\frac{+15}{-5}$ 5 kg minimum to scratch or mar	Erosion area films Nonerosion area films
1.25 Uniformity	Visual inspection	Uniform in quality, free from foreign materials, wrinkles, folds, scratches, creases or other defects.	All films

Table 8. Advanced Tests – Coating and Film Candidates

Test	Procedure	Target requirements	Test applicable to
2.1 Fluid immersion	FTMS 141, Method 6011 Exposure to the following fluids for 30 days at room temperature: a) Synthetic hydraulic fluid (Monsanto Standard Density Aviation Hydraulic Test Fluid-Low Density) b) Jet fuels - test fluid TT-S-735, Type VII c) Engine oils, MIL-L-23699	No blistering, wrinkling or other visible defects. Record pencil hardness of coatings and compare with dry pencil hardness (see 1.6)	a) Nonerosion resistant areas coatings and films. b) All materials c) All materials
2.2 Cleaning and de-icing solutions	Paint softening test procedure paragraph 12.2, D6-17487 (appendix B) a) Cleaning solution: mix one part by volume GMC 528B water base alkaline cleaner or one selected from BAC 5744, paragraph 3a (appendix B), with two parts water and 5-6 parts BMS 3-2 solvent. b) De-icing solution: (1) MIL-A-8243 (2) Hot water	No blistering, wrinkling or other visible defects. Evaluate per paragraph 12.2, D6-17487.	All materials
2.3 Operational erosion resistance	390 mph 1 in./hr 1 mm diameter simulated rainfall	400-hr goal. Record time to failure (penetration) and surface finish before, after and at intervals during test (see test 1.15)	Erosion area coatings or films
2.4 Precondition erosion test	Expose rain erosion resistant panels to accelerated weathering according to FTMS 141, Method 6152 for 500 hr. Test per 2.3.	Evaluate per 2.3. Record any reduction in performance.	Erosion area coatings or films
2.5 Erosion adhesion	Determine erosion rate of partially coated specimen per BMS 10-79, Procedure 7.2.14 (appendix B) except use candidate coating and AVCO whirling arm.	No erosion greater than 1/4 in. in length into the coated area	Erosion area coatings or films
2.6 Corrosion (salt spray)	FTMS 141, Method 6061. 1500 hr at 3% salt concentration inclined at 6° from the vertical. Scribe panels from corner to diagonal opposite corners. Also, form film coated panels using Olson Ball test equipment and test as above.	No corrosion extending more than 1/8 in. beyond the scribe mark after 1500 hr duration. No corrosion. No damage to films after wiping with MEK or after vapor degreasing.	All materials All film materials
2.7 Corrosion (exfoliation)	Appendix B	Exceed performance of baseline coating system	All coating systems
2.8 Accelerated weathering	FTMS, Method 6152 1000 hr	No checking, cracking, embrittlement, loss of adhesion or resiliency. Reduction of gloss and slight chalking acceptable.	All materials
2.9 Humidity condensing	FTMS 141, Method 6201 120°F, 30 days	No corrosion blistering, loss of adhesion, or other visible defects after 30 days.	All materials
2.10 Temperature shock	Subject to 24 cycles of 160°F (25 min.) to -65°F (5 min.) and subjected to a mandrel bend test.	The applied material will show no cracking, peeling, or loss of adhesion.	All materials
2.11 Temperature altitude	MIL-STD 810, Method 504	No loss of adhesion, blistering, wrinkling or other visible defects.	All materials
2.12 Ozone	Test "as is" specimens, specimens water-soaked for 70 ± 2 hr at 140°F and specimens exposed in weatherometer per ASTM D750 and ASTM D749. Elongate specimens 25% and test in Oreo Generator (Model 0300) at 6 ppm (parts per million) ozone concentration for 4 hr minimum.	Specimens will show no visible signs of cracking, crazing, or pitting.	All polyurethane and other rubber based materials

Table 8. Advanced Tests – Coating and Film Candidates (Cont'd)

Test	Procedure	Target requirements	Test applicable to
2.13 Impact flexibility	FTMS 141, Method 6226	No cracking or loss of adhesion.	All materials
2.14 Abrasion	ASTM C501 or FTMS 406, Method 1091 except use CS-10 wheels and 500 g weights per wheel	0.035 g maximum weight loss per 1000 revolutions	Nonerosion area materials
2.15 Tensile elongation and modulus	a) ASTM 2370 b) Heat age for 72 hr minimum at 212°F (+4°) per ASTM D573. Test per ASTM D412.	No requirement. Record data for ranking of materials.	a) All coating materials b) All film materials
2.16 Fungus resistance	MIL-STD-810, Method 508 or equivalent	Material shall not support fungus growth. Vendor certification satisfactory.	All materials
2.17 Thermal conductivity	ASTM C177	Record for de-icing analysis	All leading edge materials
2.18 Repair	Expose to accelerated weathering per FTMS 141, Method 6152 for 500 hr. Repair and determine peel, adhesion and rain erosion resistance (see 1.13, 1.17, 1.8, 1.9 and 2.5)	See 1.13, 1.17, 1.8, 1.9 See 2.5	All materials Erosion area materials

4.2.3 Candidate Materials

The large number of coating, film, and adhesive materials, including variations in the formulations of similar materials by different suppliers, prohibited the investigation of all materials and combinations. Therefore, candidates for initial screening tests were selected from each of the generic categories whose characteristics are discussed below:

Coating Candidates

1. Polyurethane elastomers

Polyurethane elastomers are the most resistant to rain erosion of the coatings currently available (see fig. 5). These coatings are currently used on commercial and military aircraft, primarily on epoxy glass radomes, but also on some leading edges. Coating smoothness is less than for polyurethane enamels. Corrosion protection is satisfactory (discussed in sec. 4.3.2.9—Corrosion Exposure).

2. Fluoroelastomers

These coatings are primarily noted for their higher temperature resistance. Surfaces are smooth and slick. Material is easy to repair, and is available in a one-component system. Based on accelerated rain erosion tests, fluorocarbons have less rain erosion resistance than polyurethane elastomeric coatings.

3. Silicone

Silicone coatings are easy to apply and maintain. Their slick surfaces may reduce drag. Resistance to fluids, chemicals, ultraviolet radiation and weathering is excellent. Silicone coatings have shown poor rain erosion resistance in accelerated tests at 224 m/s (500 mi/h). However, in flight services tests on engine cowls, they have withstood over 2500 flight hours.

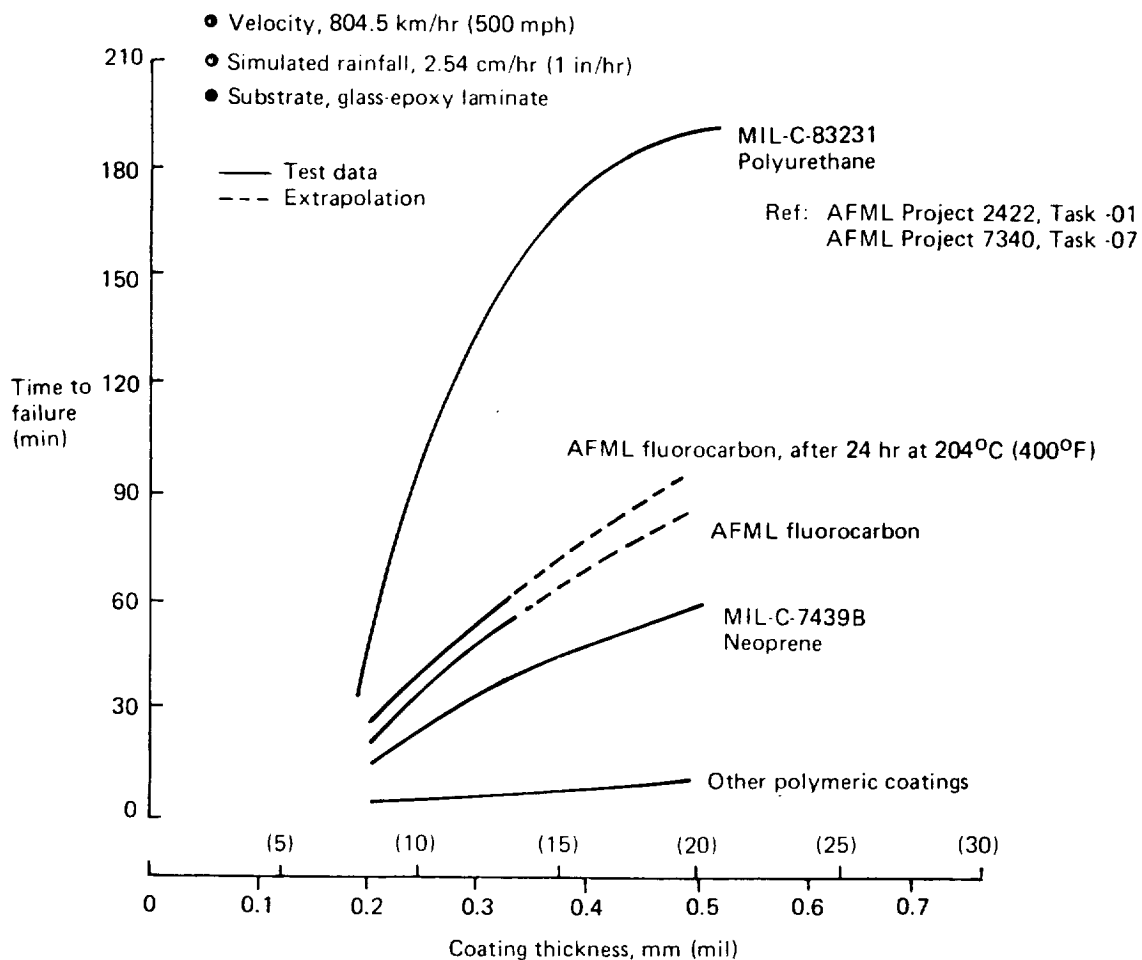


Figure 5. Comparison of Polymeric Coatings—AFML Rain Erosion Tests

4. Polyurethane enamels

Polyurethane enamel currently is applied to 727 exterior surfaces for corrosion protection. Polyurethane enamels are flexible and have excellent color and gloss retention. They are resistant to abrasion, ultraviolet radiation, and fluids, and have excellent weather durability. Rain erosion resistance is poor. The polyurethane system currently in use was included only as a baseline control to evaluate corrosion protection provided by candidate films and coatings.

5. Flexibilized epoxy

A 3M Company experimental coating has been developed that shows improved flexibility, color, and gloss retention. Rain erosion resistance is less than for polyurethane elastomeric coatings. Flight service tests for rain erosion resistance currently are being conducted on cargo aircraft. The increased flexibility may provide increased corrosion protection, as compared to conventional epoxy systems. The coating may provide a system adaptable to leading edges and wing surfaces.

Film Candidates

1. Fluoroplastic films
Films produced from fluorine-containing monomers have inherent flexibility, chemical resistance, impact strength, abrasion resistance, and high tensile strength. These properties are retained over a broad temperature range. Fluoroplastic films form smooth surfaces; however, they tend to be inert to adhesives, requiring special treatments and/or specialty adhesives to achieve adequate bonding.
2. Nitrile rubber
Nitrile rubber is a copolymer of a diene and an unsaturated nitrile. Materials with high acrolonitrile content have high tensile strength, good abrasion resistance, and oxidation resistance. Nitrile rubber has been used successfully as radome boot material.
3. Polyimide-nylon film
Nylon film has high tensile strength, good impact strength, chemical resistance, and abrasion resistance over a wide temperature range. The film is watertight and has good clarity. The film presents bonding problems and its properties vary with moisture content.
4. Polyimide-Kapton film
Kapton film is tough, flexible, and has good resistance to chemicals and ultraviolet light. It has high tensile and impact strength plus high resistance to tear initiation. Kapton film presents some bonding problems, is yellow-brown in color, and is relatively expensive.
5. Polyester film
Polyester film has high tensile strength and dimensional stability, high clarity, and good chemical resistance. The film is reasonable in cost and readily available, but it presents some bonding problems. The material is available in various widths and thicknesses.
6. Polyethylene film
Polyethylene film is available in many grades and a wide range of sizes. Ultrahigh molecular weight (UHMW) materials provide high impact strength and good mechanical properties. Polyethylene film is reasonable in cost, high in clarity, and readily formed. It presents some bonding problems. It is used in industry in high-erosion areas such as coal chutes and endless belts.
7. Polyolefin film
Ultrahigh molecular weight polyolefin film has a high impact resistance, tensile strength, and resistance to chemicals. This film has erosion resistance characteristics similar to those of UHMW polyethylene.
8. Polyparabanic acid film-Tradlon
This film is a new product of Exxon Chemical Company. Its properties approach the properties of polyimide film with an expected cost approximately 50% that of Kapton. Tradlon film presents some bonding problems and is yellow-brown in color. It was evaluated as a competitor to Kapton (polyimide) film.

9. Polypropylene film - ethylene propylene, BMS 1-50
This film has high chemical resistance, low haze, scuff resistance, toughness, and stiffness. The film must be pigmented to obtain good ultraviolet resistance, has poor low-temperature strength, and presents a bonding problem. It is used as a seal in high-erosion areas of current airplanes.
10. Polyurethane films
These films have high tensile strength and tear strength, are extremely tough, have good abrasion and impact resistance, and good chemical resistance. Polyurethane-coated fabrics are used as conveyor belts. Polyurethane films can be bonded with adhesives but the solvents pass through the film very slowly, necessitating a long cure time. Adhesive-coated tapes and sheet materials are available in a variety of thicknesses.
11. Silicone - BMS 1-57
This material has superior tear resistance and resilience. It is not affected by weathering. The material is used as a seal throughout current airplanes, but its ability to withstand high-erosion forces is unknown at this time. (Testing in this environment is necessary to determine suitability as a leading-edge candidate.)

4.3 MATERIALS AND PROCESS TESTING

Two basic types of material systems application were selected as the most promising solutions to improve leading-edge protection and to reduce surface drag. These were sprayed liquid coatings and adhesively bonded films. A total of 15 sprayable liquid coating materials were found to be available. Of these, nine were selected for evaluation, as shown in table 9. Of a total of 17 films, the 11 presented in table 10 were selected as candidates. Some of the films were obtained with an adhesive backing; the remaining films required application of an adhesive to provide the bond. All of the 13 available adhesives (also shown in table 10) were evaluated, to provide a minimum of two adhesives for each free film.

Table 9. Liquid Coating Concepts Selected for Evaluation

Concept	Coating	Designation	Source
21	Polyurethane	B-274	CAAPCO
22	Polyurethane	Experimental	CAAPCO
23	Epoxy (flexible)	Experimental	3M Company
24	Fluoroelastomer	Type II	CAAPCO
25	Silicone (clear)	DC 3145	Dow Corning
26	Polyurethane	Astrocoat (MIL-C-83231)	Sterling
27	Polyurethane	BMS 10-60	Desoto
28	Polyurethane	M313 (Chemglaze)	Hughson
29	Silicone	Dapcoat 3400 CS	D. Aircraft Products

Table 10. Films and Adhesives Selected for Evaluation

Film Candidates		
Material	Designation	Source
Polyurethane	Hituff	J.P. Stevens
Polyurethane (adhesive-backed)	3M 8562	3M Company
UHMW Polyethylene	—	Dupont
UHMW Polyethylene (adhesive-backed)	—	Taconic
UHMW Polyolefin (adhesive-backed)	—	Taconic
Polyester (elastomeric)	Hytrel	Dupont
Polyester (adhesive-backed)	3M 5690	3M Company
Polyimide	Kapton	Dupont
Polyimide (adhesive-backed)	—	Taconic
Polyvinylidene fluoride (PVF ₂)	Kynar 500	Rexham
Polyparabanic acid	Tradlon	Exxon
Adhesive Candidates		
Material	Designation	Source
Polyurethane (flexible)	DPAD 6298	Conap
Polyurethane	RP 6401	Ren Plastics
Polyurethane	DA 552-1	Ren Plastics
Polyurethane (phenolic-modified)	7124	Bostik
Polyester	56065	Dupont
Polyester	7064	Bostik
Polyester	7132	Bostik
Nitrile rubber	4045	Bostik
Fluorocarbon	Adhesive 80	Fluoroplastics, Inc.
Polysulfide	PR 1422	Products Research
Epoxy polyamide	BMS 5-29 (Avco M73040)	Miller-Stephenson
Acrylic	Conastic 830	Conap
Silicone	Densil 3078	Dennison

The original test plan was to subject these materials to a number of screening tests, select five concepts, and thoroughly evaluate these five in advanced tests. Very early during the screening tests, however, problems were encountered in satisfactorily bonding the film materials, resulting in 60 film/adhesive combinations being tested. Target peel strength requirements were established as 1.79 and 0.54 kg/cm (10 and 3 lb/in) for erosion area coatings and nonerosion area coatings, respectively. A large number of adhesive peel tests were performed in order to select a minimum of two adhesives for each film material. The two test phases were thus redefined, with the objective of the first phase becoming the identification of adhesive materials with which to bond the films. The large number of film/adhesive candidates emerging from the screening tests required that the advanced testing be initiated with a much larger list of candidates than originally planned. In addition, many screening tests were actually continued during advanced testing. Adhesion of the sprayed coatings was judged satisfactory because the peel specimens failed in cohesion within the coating materials, indicating that the bond had greater strength than the coating itself.

4.3.1 Screening Tests

The basic screening approach to select materials for advanced evaluation was to subject them to adhesion tests and to tests for adhesion after fuel immersion. Adhesive-free films (films manufactured without adhesive backing) presented in table 10 were bonded to 2024-T3 alclad aluminum substrates using adhesives selected from table 10.

In each case, a peel panel (ref. ASTM D903) large enough to provide six peel tests was fabricated. After the prescribed cure time, three virgin peel tests were performed. The remainder of the panel was then exposed to jet fuel for 24 hr. The specimens were removed from the jet fuel, excess fuel was removed, and the specimens were peel tested as before. The tabulation of film/adhesive combinations and test results are presented as table C-1 in appendix C.

The selection of film/adhesive candidate concepts for advanced testing was based upon both the virgin and exposed peel strengths. Of the original 13 adhesives, six were selected for further evaluation in combination with the five film candidates that require an adhesive. These concepts are listed in table 11. A summary of the test results of film/adhesive concepts selected for further evaluation is presented in table 12. In each case, at least two adhesives per film were selected for further evaluation.

The UHMW polyethylene adhesive-backed film candidate was deleted from further tests due to difficulties in achieving satisfactory initial adhesion. The polyurethane RP 6401 adhesive candidate specimens were of very poor quality. The cause is attributed to the adhesive batch. Time did not permit ordering new adhesive material; therefore, the investigation of this candidate was terminated.

4.3.2 Advanced Tests

Advanced testing was initiated with a much larger list of candidates than originally planned. These candidates consisted of the nine liquid coating materials identified in table 9 and the 16 film/adhesive concepts shown in table 11.

The screening test program for the liquid coating materials is defined in table 6. The program for the free films and adhesives is defined in table 7. The advanced tests for all concepts are defined in table 8. Each of these tables includes the test description or environment, the procedure used, and the location of the detail test results. Based on the test results, seven concepts were selected for further evaluation. A summary of the performance of these seven materials is presented in table 13.

The advanced test program consisted of two basic categories of tests: environmental exposure and performance characterization. To evaluate each concept, virgin performance characterizations were performed. Following environmental exposure, selected performance characterization tests were repeated to ascertain the effect of the environment. Whenever possible standard tests, as defined by the American Society for Testing and Materials (ASTM) or federal test methods, were utilized. Table 14 shows the sequential nature of much of the testing. The following discussion of test results is referenced to the sequence in table 14.

Table 11. Film/Adhesive System Concepts Selected for Advanced Testing

Concept	Film	Adhesive	
I	Kapton (polyimide)	PR 1422	(polysulfide)
II	Hytrel (polyester elastomer)	PR 1422	(polysulfide)
III	Tradlon (polyparabanic acid)	PR 1422	(polysulfide)
IV	Hytrel (polyester elastomer)	DP AD 6298	(polyurethane)
V	Tradlon (polyparabanic acid)	DP AD 6298	(polyurethane)
VI	Hituff (polyurethane)	DP AD 6298	(polyurethane)
VII	Hituff (polyurethane)	Bostik 7064	(polyester)
VIII	UHMW Polyolefin	Silicone	(adhesive-backed)
IX	Kapton (polyimide)	Dupont 56065	(polyester)
X	Hytrel (polyester elastomer)	Dupont 56065	(polyester)
XI	Kynar (polyvinylidene fluoride)	DA-552-1	(polyurethane)
XII	Kynar (polyvinylidene fluoride)	Adhesive 80	(fluorocarbon)
XIV	3M 8561 (polyurethane)	Acrylic	(adhesive-backed)
XV	3M 5690 (polyester)	Acrylic	(adhesive-backed)
XVI	Kapton (polyimide)	Acrylic	(adhesive-backed)
XVII	Kapton (polyimide)	Silicone	(adhesive-backed)

Table 12. Peel Strengths of Selected Film/Adhesive Concepts

Adhesive	Appearance	Film	Peel strength—average of 3 specimens	
			Initial kg/cm (lb/in)	After fuel immersion kg/cm (lb/in)
PR 1422 PS	Very good	Kapton	1.61 (9)	1.61 (9)
56065 PE and primer	Fairly good	Kapton	1.61 (9)	1.25 (7)
PR 1422 PS	Fairly good	Hytrel	2.32 (13)	0.18 (1)
DP 6298 Urethane	Good	Hytrel	1.25 (7)	0.89 (5)
56065 Polyester	Good	Hytrel	0.54 (3)	1.23 (7)
PR 1422 PS	Fairly good	Tradlon	1.61 (9)	1.25 (7)
DP 6298 Urethane	Very good	Tradlon	1.79 (10)	0.36 (2)
7064 Polyester	Very good	Hituff	0.80 (4.5)	0.62 (3.5)
Ren DA552-1	Good	Kynar	1.00 (5.6)	1.28 (7.1)
Adhesive 80	Very good	Kynar	0.89 (5)	0.27 (1.5)
Taconic 6311	Very good	Polyolefin	1.25 (7)	— (—)
DP6298 Urethane	Very good	Hituff	0.80 (4.5)	0.80 (4.5)

Table 13. Summary of Environmental Test Results (Subjective)

Concept	Film/ Adhesive	Adhesion peel kg/cm (lb/in)	30-day water 60°C (140°F)	30-day fuel room temp	7-day hydraulic fluid 49°C (120°F)	30-day hydraulic fluid room temp	30-day engine oil room temp	30-day alkaline cleaner room temp	42-day accelerated weathering	62-day salt spray room temp	Temperature/ altitude
I	Kapton PR 1422	0.86 (4.8)	Good	Slightly affected	Good	Good	Good	Good	Good	Good	Good
III	Tradlon PR 1422	1.79 (10)	Good	Good	Good	Good	Good	Good	Good	Reduced adhesion	Affected
VIII	UHMW polyolefin adhesive-backed	1.25 (7)	Good	Bond failure	Good	Good	Good	Good	Good	Good	Slightly affected
XII	Kynar 500 Adhesive 80	0.54 (3)	Good	Bond failure	Good	Affected	Good	Good	Good	Good	Good
21	CAAPCO Polyurethane	*	Slightly affected	Good	Dissolved	Dissolved	Good	Good	Good	Good	Good
26	Sterling Astrocoat	*	Slightly affected	Good	Dissolved	Dissolved	Good	Slightly affected	Good	Good	Good
28	Hughson Chemglaze	*	Affected	Good	Dissolved	Dissolved	Good	Good	Good	Good	Good

*Tensile failure of coating

Table 14. Test Plan for Measurement of Performance Characteristics

Test item No. *	Environmental exposures	Test procedure	1.25	1.11	1.7,1.8,1.13	1.14	1.10	2.13		2.12	2.14	1.24	1.16	1.16	1.23
			Visual	Pencil hardness 7.2.5 ^d	Peel tests D-903 ^b	Rain erosion 7.2.14 ^d	Flexibility	D522 ^b	6226 ^a	Ozone elongation	Abrasion C501 ^b	Hardness Shore A	Tensile D2370 ^b	Tear D624 ^b	Shrinkage
1.12	Virgin properties		X	X	X	X	X	X	X	X	X	X	X	X	X
1.21	Fluid immersion	6011 ^a	X	X	X	X	X	X	X	X	X	X	X	X	X
2.1	Jet fuel	1 day	X	X	X	X	X	X	X	X	X	X	X	X	X
1.12	Hydraulic fluid	30 days	X	X	X	X	X	X	X	X	X	X	X	X	X
1.21		7 days	X	X	X	X	X	X	X	X	X	X	X	X	X
2.1		30 days	X	X	X	X	X	X	X	X	X	X	X	X	X
2.1	Engine oil	30 days	X	X	X	X	X	X	X	X	X	X	X	X	X
2.1	Alkaline cleaner	30 days	X	X	X	X	X	X	X	X	X	X	X	X	X
2.2	Deicing solution	30 days	X	X	X	X	X	X	X	X	X	X	X	X	X
2.2	Water	1 day	X	X	X	X	X	X	X	X	X	X	X	X	X
1.20	Hot water	30 days	X	X	X	X	X	X	X	X	X	X	X	X	X
2.2		3 days	X	X	X	X	X	X	X	X	X	X	X	X	X
2.14			X	X	X	X	X	X	X	X	X	X	X	X	X
1.18	Temperature/Humidity		X	X	X	X	X	X	X	X	X	X	X	X	X
2.11	Dry heat	D573 ^b	X	X	X	X	X	X	X	X	X	X	X	X	X
2.11	Temperature/altitude	504 ^c	X	X	X	X	X	X	X	X	X	X	X	X	X
2.10	Temperature/shock		X	X	X	X	X	X	X	X	X	X	X	X	X
2.9	Humidity	6201 ^a	X	X	X	X	X	X	X	X	X	X	X	X	X
1.19	Weatherometer	6152 ^a	X	X	X	X	X	X	X	X	X	X	X	X	X
2.4		12 days	X	X	X	X	X	X	X	X	X	X	X	X	X
1.19		21 days	X	X	X	X	X	X	X	X	X	X	X	X	X
1.19		42 days	X	X	X	X	X	X	X	X	X	X	X	X	X
2.6	Corrosion	6061 ^a	X	X	X	X	X	X	X	X	X	X	X	X	X
2.7	Salt spray	B287 ^b	X	X	X	X	X	X	X	X	X	X	X	X	X
2.7	Exfoliation		X	X	X	X	X	X	X	X	X	X	X	X	X

* Test item No. per tables 6, 7, and 8

^aFTMS 141 method

^bASTM

^cMIL-STD-810

^dBoeing procedure BMS-79

4.3.2.1 Specimen Preparation

In the preparation of the many test panels for advanced testing, it was necessary to establish procedures for substrate cleaning, for application of the spray coating, and for adhesive bonding of the film materials. The substrate material used throughout this program was 2024-T3 alclad aluminum. The procedure for preparing this substrate consisted of cleaning with an alkaline solution such as Alkanox and an abrasive pad such as Scotchbrite. The cleaned, rinsed, and dry surface was then alodined. In preparation for the sprayed coatings, the substrate was primed with either MIL-P-23377 or BMS 10-79 primer. In the case of the bonded films, both unprimed substrates and substrates primed with MIL-P-23377 were evaluated with selected adhesives. The processes for surface preparation, spray application of selected coatings, and bonding of the films are outlined in appendix D.

4.3.2.2 Basic Properties

Physical Appearance

A visual examination was conducted to subjectively evaluate the smoothness and surface characteristics of the sprayed and bonded material candidates. Evaluations were made on a scale of excellent, very good, good, fair, poor. The results of this examination are presented in table 15.

The polyurethane spray coatings, concepts 21, 22, 26, 27, and 28 were all judged very good in surface smoothness and appearance. The surfaces had the friction characteristics of hard rubber and were not as slick to the touch as were the films. Of these concepts, Astrocoat seemingly had the highest surface friction. A fluoroelastomer coating (concept 24) and a silicone coating (concept 29) were rated good, both exhibiting minor surface defects. A second silicone coating (concept 25) was not received as a sprayable coating and required considerable thinning and experimentation in order to spray properly. Attempts to achieve a sprayable solution were not satisfactory and concept 25 was deleted from the program. Material for concept 23, an experimental flexible epoxy, was not received in time to be evaluated.

The appearance of all Kapton (polyimide bonded film specimens (concept I, IX, XVI, and XVII)) was rated excellent. Kapton film was applied using four different adhesives, two of which were supplied as adhesive backings on the Kapton. In all cases, the surfaces were smooth with minimal surface depressions or defects. The Tradlon (polyparabanic acid) bonded film (concepts III and V) were rated very good in appearance, just below the Kapton films. Materials rated good in appearance and smoothness included Kynar when bonded with a polyurethane and a fluorocarbon adhesive (concepts XI and XII) and concept VIII, a UHMW polyolefin supplied with a silicone adhesive backing. The two polyurethane specimens (concepts IV and X) were rated fair, and were of considerably lower quality than the preceding materials. One concept, Hytrel bonded with a polysulfide adhesive (concept II), was not acceptable from a surface smoothness consideration and was rated poor.

In general, the films can be classified as either relatively hard, high modulus, elastic materials (Kapton, Tradlon, Kynar, UHMW polyolefin); or relatively soft, low modulus, elastomeric materials (Hytrel and Hituff). The high modulus films are typically very smooth or slick to the touch (have an apparently low friction coefficient), while the elastomeric materials are smooth, but not slick.

Table 15. Visual Examination Results

Concept	Coating material	Adhesive	Visual appearance and smoothness*
21	CAAPCO B-274 polyurethane	—	Very good
22	CAAPCO experimental polyurethane	—	Very good
24	CAAPCO fluoroelastomer	—	Good
26	MIL-C-83231 Astrocoat polyurethane	—	Very good
27	BMS 10-60 polyurethane	—	Very good
28	Hughson M313 polyurethane	—	Very good
29	Dapcoat 3400 CS silicone	—	Good
I	Kapton (polyimide)	PR 1422 polysulfide	Excellent
II	Hytrel (polyester elastomer)	PR 1422 polysulfide	Poor
III	Tradlon (polyparabanic acid)	PR 1422 polysulfide	Very good
IV	Hytrel (polyester elastomer)	DP AD 6298 polyurethane	Fair
V	Tradlon (polyparabanic acid)	DP AD 6298 polyurethane	Very good
VI	Hituff (polyurethane)	DP AD 6298 polyurethane	Fair
VII	Hituff (polyurethane)	Bostik 7064 polyester	Fair
VIII	UHMW Polyolefin	Silicone adhesive-backed	Good
IX	Kapton (polyimide)	DuPont 56065 polyester	Excellent
X	Hytrel (polyester elastomer)	DuPont 56065 polyester	Fair
XI	Kynar (polyvinylidene fluoride)	DA 552-1 polyurethane	Good
XII	Kynar (polyvinylidene fluoride)	Adhesive 80 fluorocarbon	Good
XVI	Kapton (polyimide)	Acrylic adhesive-backed	Excellent
XVII	Kapton (polyimide)	Silicone adhesive-backed	Excellent

*Scale: Excellent, very good, good, fair, poor.

The high modulus films tend to hide any nonuniformities of the substrate and adhesive layer, and retain the surface character of the film material. The elastomeric materials have a tendency to gather or wrinkle when bonded, and are less capable of hiding subsurface imperfections. The elastomers also tend to retain dust particles, while the high modulus films are readily wiped clean.

The Hytrel film samples were warped as supplied and would not lie flat. This resulted in a poor appearance of bonded samples, which may not be typical of this material.

Smoothness Tests

Surface smoothness profiles for the film and coating candidates were made with a Taylor-Hobson model 3 Talysurf profilometer. This instrument traces the surface with a diamond tip having a radius of about $1.27\text{ }\mu\text{m}$ ($50\text{ }\mu\text{in}$). It is easily capable of detecting roughness amplitudes of 0.025 mm (1 mil) at peak-to-peak distances of less than 0.127 mm (5 mil).

Figure C-1 (appendix C) presents surface profiles for the film materials. Smoothness characteristics of the Kynar, Tradlon, UHMW polyolefin, and the 3M films are excellent—at or beyond the capability of the instrument. The Kapton film had barely detectable roughness, while the Hituff and Hytrel films had definitely detectable amplitudes.

The sprayed polyurethane erosion coatings all had barely detectable roughness characteristics with the Sterling Astrocoat being slightly rougher than the others. The smoothness of the DeSoto BMS 10-60 was excellent, beyond the limit of the instrument. The CAAPCO Type II fluoroelastomer had barely detectable roughness and the Dapcoat 3400-S silicone was the roughest of the sprayed coatings. Surface profiles for the sprayed coatings are shown in figure C-2 (appendix C).

Abrasion Resistance

Abrasion tests were performed by mounting 10.16 cm (4 in) square coated specimens in a holder capable of being rotated in a horizontal plane. Two weighted abrasion wheels were positioned vertically on either side of the specimen center point, and the specimen was rotated through 1000 rev. Weight loss to the specimen coating was measured at the end of the test. The testing, using a Tabor abrading machine, was done in accordance with ASTM C501, except that C S-10 wheels were used with a 500g load applied to each wheel.

Only one silicone material, concept 29, with a weight loss of 0.110g exceeded the maximum allowable loss of 0.035g/1000 rev. The majority of the remaining materials did not exceed 0.010g/1000 rev. The abrasion resistance test data are reported in appendix C, table C-4.

Film Shrinkage

The free-film shrinkage test consisted of placing a $15.24 \times 15.24\text{ cm}$ (6 x 6 in) specimen in an air circulating oven at a temperature of $132 \pm 2.8^\circ\text{C}$ ($270 \pm 5^\circ\text{F}$) for 10 min. The target requirement allowed shrinkage of less than 5%. Only the Hituff with 7.4% shrinkage did not pass this test. The shrinkage test results are presented in appendix C, table C-3.

Impact Flexibility

The impact flexibility tests were performed in accordance with Federal Test Method Standard 141a, Method 6226, except that the substrates were 2024-T3 alclad aluminum. The test consists of placing a 30-31 gage coated metal plate, coating downward, on a rubber pad and dropping an impactor on the plate. Impactor ends are reversed and it is dropped a second time on an area adjacent to the first impact. Percent elongation or flexibility is measured at the highest area of distensibility in which the coating remains intact. The target requirement was that no cracking or loss of adhesion should occur.

Five concepts did not pass this test. Concept III (adhesive-backed polyolefin), concept IX (Kynar/polyurethane), and concept XII (Kynar/adhesive 80) debonded. Concept XV (3M 5690 polyester, adhesive-backed) and concept 27 (BMS10-60, polyurethane) resulted in film failure. The remaining concepts passed this test. Results are shown in appendix C, table C-4.

4.3.2.3 Fluid Immersion

The fluid immersion testing was performed in accordance with Federal Test Method Standard 141, Method 6011. Test panels were immersed in the test fluid in a vertical position. After exposure for the time intervals prescribed in table 14, the specimens were extracted from the bath, excess fluid removed, a visual examination conducted, and the pencil hardness checked. In addition, peel strength tests (ASTM D903) were performed on specimens exposed for 1 day to jet fuel and water. Samples exposed to 7 days immersion in hydraulic fluid were also subjected to peel testing.

The individual fluids and exposure times are listed in table 14. It should be noted that the 30-day immersion is a very severe test. In addition, the test specimens were not protected at the edges as they would be in applications to aircraft. Test results are presented in tables C-5 and C-6 of appendix C.

A discussion of the test results follows:

Jet Fuel (TT-S-735, Type VII)

Only four concepts completely survived the 30-day jet fuel immersion. They are concept III (Tradlon/PR 1422), concept XV (3M 5690 AB), concept 21 (MIL-C-83231, CAAPCO polyurethane) and concept 21 (BMS 10-60, polyurethane paint). The remaining concepts ranged from slightly affected—for concepts I, IX, XIV, 22, 24, and 28—to complete debond for the remaining concepts.

Hydraulic Fluid

Only four concepts completely survived the 30-day immersion in hydraulic fluid. They are concepts I, III, VIII, and IX. The polyurethane film (Hituff) dissolved in 1 day, while the spray coatings of polyurethane dissolved in 2 days. This difference in time is attributed to material thickness. The polyurethanes, except for BMS 10-60, Types I and II, are quite susceptible to hydraulic fluid damage.

Engine Oil (MIL-L-23699)

The concepts employing polyurethane films performed very well under engine oil immersion except for concept VI, (Hituff) with the polyurethane adhesive. However, this failure is attributed to wrinkles in the Hituff material, allowing seepage of the fluid. The remaining concepts performed well with some slight effect observed in concepts II, IV, VIII to XII, XVI and concept 29.

Alkaline Cleaner (Per BAC 5744)

The six concepts that failed this exposure were IV, V, VII, IX, X, and XIV. The majority of these concepts were polyesters. The remaining concepts were unaffected or only slightly affected.

Deicing Solution (MIL-A-8243)

The only concept significantly affected by the deicing solution was concept XI, a polyvinylidene fluoride (Kynar) with a polyurethane (DA 552-1) adhesive bond.

Water (Room Temperature and Hot)

Generally, the concepts containing polyurethane were affected to some degree by long-term exposure to water at 60°C (140°F). Only one complete debond occurred, that being concept V (Tradlon/ DPAD 6298). The remaining specimens exhibited good resistance to water immersion.

4.3.2.4 Heat Aging

Accelerated aging by the oven method was conducted in accordance with ASTM D573. The test specimens were suspended vertically and separated from each other and from the sides of the chamber. The specimens were aged at $71 \pm 2.8^\circ\text{C}$ ($160^\circ \pm 5^\circ\text{F}$) for 7 days. After aging, visual examination and peel, film hardness, film tensile, and film tear tests were conducted. Results are shown in table C-3, appendix C.

The dry heat aging did not change the film hardness. No visual effects were noted. The only significant change in physical properties was a 50% reduction in tensile strength for the Hytrel. The remaining material showed either the same or slightly improved properties.

4.3.2.5 Temperature and Altitude

The effects of temperature and altitude were simulated based upon MIL-STD-810, method 504, category 5. Test results indicated the majority of the concepts exhibited either no change or improved peel strengths. The exceptions being concept III (Tradlon/PR 1422), concept VI (Hituff/DPAD 6298), and concept XI (Kynar/DA552-1).

4.3.2.6 Temperature Shock

The environmental exposure to simulate temperature shock was accomplished by subjecting test specimens to 24 cycles of 71°C (160°F) for 25 min, followed by 5 min at -54°C (-65°F). After exposure, all specimens were subjected to the flexibility tests described in ASTM D522. From these tests, elongation percentage was determined. Results showed no significant change in percent elongation. Visual examination indicated that during the flexibility test, on both the virgin and exposed samples, concepts III, V (both Tradlon) and 27 (polyurethane paint) failed by fracture of the film. A debond of the film for concept XI (Kynar with DA552-1 adhesive) occurred on the virgin tests but did not occur after exposure.

4.3.2.7 Humidity (Condensing)

The general procedure of Federal Test Method Standard 141, Method 6201 was followed for exposing film systems to a moisture-saturated atmosphere, at controlled temperature and with continuous condensation on the test surface. The test specimens were suspended in the humidity chamber in the vertical position at equal spacing. The test temperature was $49 \pm 1^{\circ}\text{C}$ ($120^{\circ} \pm 1.8^{\circ}\text{F}$) for 30 days. Following exposure, the specimens were removed from the chamber and visually inspected, and peel tests were run. The test data (table C-5) appendix C, indicated that: visually, concepts II, IV, and V showed moderate effects, while concepts X and 29 had been slightly affected. The remaining concepts were not visually affected. The peel strength for concepts III (Tradlon/PR 1422), concept VI (Hituff/DPAD 6298), concept VII (Hituff/7064), concept IX (Kapton/56065), and concept XI (Kynar/DA552-1) had significant reductions. Concepts XIV, XV, XVI, and XVII were not peel-tested due to termination of the test program.

4.3.2.8 Weatherometer

The effects of accelerated weathering were measured after exposure in the weatherometer in accordance with Federal Test Method Standard 131, Method 6152. Material specimens were mounted on racks around the circumference of the test chamber. The daily exposure cycle consisted of 18 hr of 102 min of light, followed by 18 min of a combination of light and water spray. This 18-hr period was followed by 6 hr of darkness. The weatherometer was operated 7 days per week for the total exposure times of 12, 21, or 42 days, depending upon the particular post-exposure evaluation test to be conducted.

Three sets of specimens were exposed. First, a standard peel panel of each concept was exposed for 42 days. Second, two specimens of each material, prepared for subsequent test in the rain field, were exposed for 21 days. The third set of specimens were films stripped from panels representing concepts 21, 26, and 28. These films were tested for effects of ozone after a 12-day weatherometer exposure.

Visual examination of the peel panels indicated that concepts II, IV, and X decomposed during exposure. These concepts employed Hytrel (a polyester elastomer) as the film coating. Concept IX (Kapton/56065) appeared slightly affected. The remaining concepts were unaffected. The results of the rain erosion tests after weatherometer exposure are reported in section 4.3.2.11.

4.3.2.9 Corrosion Exposure

Salt Spray

The environmental exposure condition for salt spray (fog) testing is defined in Federal Test Method Standard 141, Method 6061. Test specimens of each concept were exposed to a 3% salt concentration for 1500 hr. Each specimen was scribed diagonally from corner to corner and inclined at 6 deg from vertical, as prescribed for organic coatings in the test procedure. This inclination ensures full uniform coverage of the specimen by the salt spray that is introduced through the top of the test chamber. At the end of the specified exposure, each specimen was examined visually. The individual test results are presented in table C-6, appendix C. Two samples, concept V (Tradlon/DPAD 6298) and concept XI (Kynar/DA552-1), exhibited significant debond of the film. A moder-

ate film removal was observed on concepts III and X. Of the remaining concepts, using bonded films, only concepts I, VI, XII, XVI, and XVII were rated good.

All the spray-coated concepts appeared to be undamaged after the 62-day exposure. Concepts XIV and XV (both 3M adhesive-backed films) were not received in time to be included in this test.

Exfoliation

Exfoliation corrosion was evaluated for three polyurethane coating materials: concept 21 (CAAPCO B-274), concept 26 (Astrocoat), and concept 28 (Hughson M313). The test panels consisted of a stainless steel base plate, a 2024-T3 aluminum center plate, and a top plate of 7075-T6 aluminum. The plates were held together with countersunk titanium fasteners. The top surface was sprayed with the test coating, and edges were sealed with a polysulfide sealant. A description of the panels and test procedure is contained in appendix B. The three test panels were subjected to 30 days of acetic acid salt spray testing in accordance with ASTM B287. A 5% salt solution was prepared with the pH adjusted to a range of 3.1 to 3.3 by the addition of acetic acid. Temperature in the chamber was maintained at $35^{\circ}\text{C} \pm 0.56^{\circ}$ ($95^{\circ}\text{F} \pm 1^{\circ}$) for the period of test. The specific gravity of the solution was held between 1.0255 and 1.0400.

Following exposure, the test panels were disassembled and visually examined. No evidence of exfoliation corrosion was present on any surface, including countersunk areas and holes. Figure 6 shows the panel coated with CAAPCO B-274 disassembled following the test. Figure 6a shows the upper surfaces of the coated top plate (fasteners removed and inverted) and the center plate. Figure 6b shows the lower surfaces of the top plate (fasteners in place) and center plate, and upper surface of the base plate. Mill marks on the plates are from burr removal prior to assembly and test of the panels. The post-test condition of this panel is typical of the three test panels.

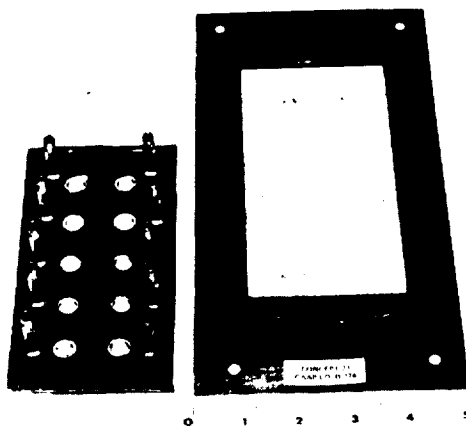


Figure 6a. Top Plate Removed

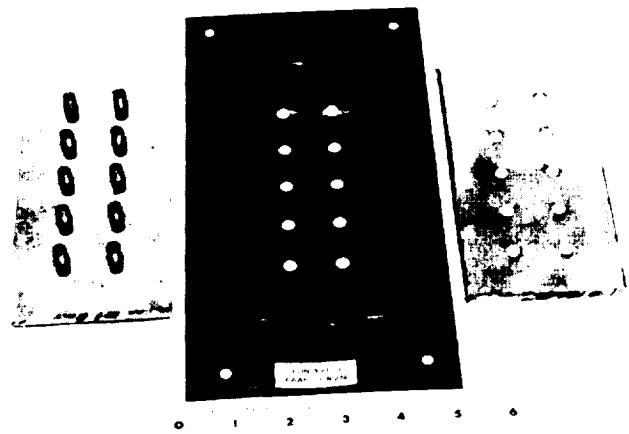


Figure 6b. Top and Center Plates Removed

Figure 6. Exfoliation Panel After Test (CAAPCO B-274 Coating)

4.3.2.10 Pencil Hardness Testing

Each virgin sample and each exposed sample was measured for pencil hardness. The test method for pencil hardness is described in Boeing Procedure BMS 10-79, paragraph 7.2.5 (appendix B). This procedure defines that a pencil, held with a firm pressure at 45 deg to the surface, be moved across the virgin and exposed samples. The hardness of pencil that first produces cutting or scratching is determined. It was found that test results were subject to operator techniques. Therefore, in order to eliminate technique differences, the same operator performed all tests. The values of relative hardness are presented in table C-7 (appendix C).

Test results showed that the majority of the films are very hard.

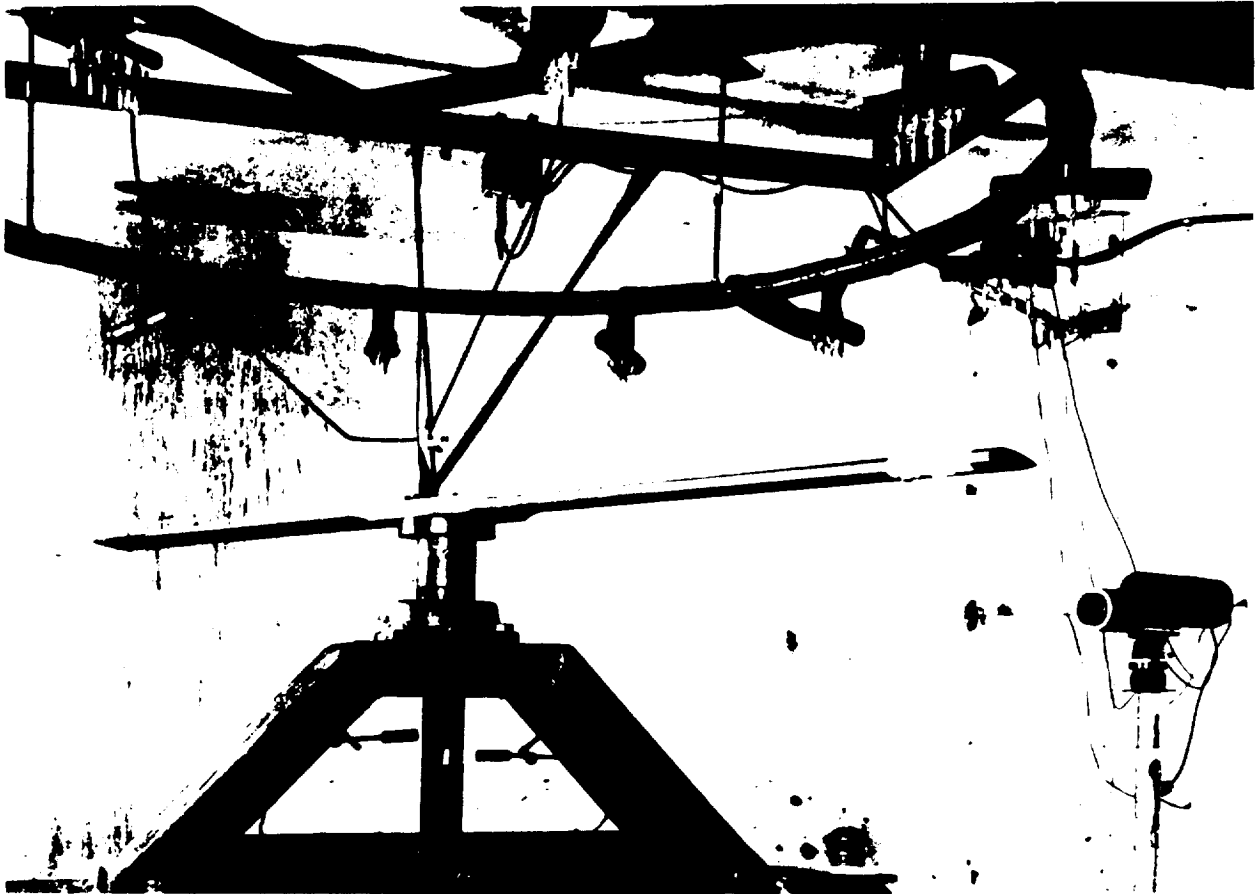
4.3.2.11 Rain Erosion

The rain erosion performance of candidate materials was a major evaluation criterion. Rain erosion testing used the Air Force Materials Laboratory rotating arm apparatus located at Avco, Wilmington, Massachusetts. This apparatus, shown in figure 7, has a 1.83m (6 ft) diameter, zero-pitch blade with cutouts on each end to accommodate 12.7-cm (5-in) long airfoil leading-edge-shaped specimens. The water system used to simulate the rain environment is mounted above the blade, and consists of groups of individually stopcocked hypodermic needles (51 total) that can be adjusted to give various simulated rainfall rates 1.27 to 7.62 cm (0.5 to 3 in) per hr with controlled drop sizes from 0.2 to 2.8 mm diameter. A motor drives the blade at 224 m/s (500 mi/hr). An eroded specimen mounted on one end of the blade is shown in figure 7.

A TV camera, monitor, and stobe unit enable the operator to observe the mode of failure and time to failure of specimens (i.e., penetration of the coating or film to the substrate) while the apparatus is running. These critical observations have been vital to the development of erosion resistant coatings for radome and other applications. The normal operation of the rotating arm involves adjusting the flow rate of each hypodermic needle in the water ring to achieve the approximate drop size and simulated rainfall rate. Two specimens are securely fastened to opposite ends of the blade. The motor voltage is adjusted to achieve a 224 m/s (500 mi/hr) tip speed, and the extent of erosion on each specimen is monitored. The test is terminated and time recorded when either or both specimens erode through the coating, exposing the substrate. When one sample has failed, it is replaced with a new sample and the testing is continued.

The rainfield to evaluate materials under this program used a 2.54 cm/hr (1 in/hr) rain rate and 0.7-mm diameter drop size. A few tests were conducted using 2-mm diameter drops to provide data for the estimated service life study reported in section 4.3.3. All tests were conducted at a velocity of 224 m/s (500 mi/hr) with airfoil substrates of etched 2024-T3 aluminum.

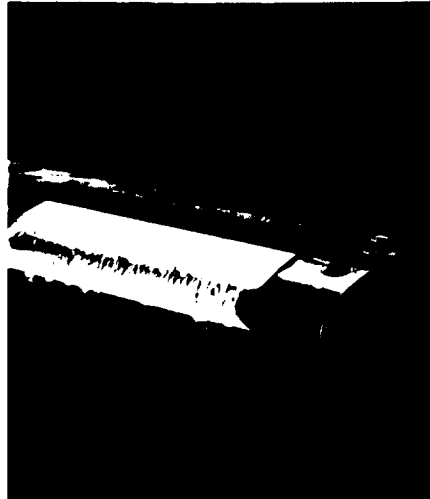
Although rain erosion performance was considered most critical for materials selected for leading-edge applications, all materials that performed well during the early stages of the advanced environmental testing were subjected to the rain tests. Materials evaluated, therefore, included films bonded onto the airfoil substrates with selected adhesives, and liquid coatings sprayed onto prime airfoil substrates.



Overall view of rotating arm apparatus showing blade, rain simulator, TV camera, and strobe unit



Bank of hypodermic needles producing simulated rainfield



Test specimen showing erosion on outboard edge



Test facility monitor and speed control

Figure 7. Rotating Arm Apparatus

The rain erosion test results are shown in table 16 for the bonded films and liquid coatings. None of the film materials tested exhibited satisfactory rain erosion resistance for leading-edge application. The most resistant of the films evaluated was Hituff polyurethane, which failed after an average of 38 min when bonded with Conap DP 6298 polyurethane adhesive. Hytrel polyester bonded with PR 1442 polysulfide adhesive failed after an average of 28.5 min. The remainder of the films failed after much shorter exposure times. Kapton polyimide, which failed after exposure times of from 1 to 3.5 min, was typical of the performance of the remainder of the film materials.

The rain erosion performance of some of the liquid coating materials far exceeded the bonded films. The most rain-resistant sprayed coating evaluated was B-274 polyurethane (concept 21), a proprietary coating manufactured by the CAAP Company, Inc. (CAAPCO). In four tests of this material, time to failure ranged from 257 to 517 min, and averaged 402 min. The material currently qualified to MIL-C-83231, Type I, is Astrocoat polyurethane, marketed by Sterling Paint company. Astrocoat failed after an average of 125 min in the rainfield. Two other materials that exhibited superior rain erosion resistance were Hughson M313 polyurethane and Experimental Black polyurethane from CAAPCO, which exhibited respective failure times of 200 min and 122.5 min.

The two most resistant materials, CAAPCO B-274 and Hughson M313, were selected with Astrocoat, which is generally considered the industry standard rain erosion coating, to be evaluated in the rain erosion facility after weatherometer exposure for 21 days. Results of these tests are shown in table 17. One of the two CAAPCO B-274 specimens failed after 210 min, and the other specimen survived for a minimum of 600 min, at which point the testing of that specimen was terminated. Since average time to failure for the unexposed material was 402 min, it was concluded that the weatherometer exposure had no effect on the rain erosion performance of CAAPCO B-274 polyurethane. Weatherometer exposure did, however, appear to reduce the performance of Hughson M313, which failed after 70 min and 103 min in the rain erosion facility, compared with 200 min for the unexposed material. The time to failure of the Astrocoat material was 94 min following weatherometer exposure, compared with an average of 125 min for the unexposed material. It was concluded that the weatherometer had little effect on Astrocoat rain performance.

To compare the rain performance of a typical aluminum material with that of the most resistant coating, a series of tests was conducted using 2024-T3 aluminum specimens mounted on one end of the rotating blade and CAAPCO B-274 coated specimens on the other end. These specimens were then tested in the standard rainfield 2.54 cm (1 in) per hr, 0.7 mm diameter drops, at 224 m/s (500 mi/hr). Two tests were conducted in this manner, and the times to failure for the aluminum as defined by significant surface pitting and roughening were 95 min in both cases. The first CAAPCO B-274 panel survived to 257 min, and the second to 398 min.

4.3.2.12 Ozone Resistance

Ozone resistance was evaluated by elongating the specimens 25% and exposing them to an ozone concentration of six parts per million for 4 hr. Three polyurethane coating materials were tested: concept 21 (CAAPCO B-274), concept 26 (Astrocoat), and concept 28 (Chemglaze M313). In each case, virgin specimens, specimens previously exposed to a 12-day weatherometer cycle, and specimens previously water immersed for 72 hr at 60°C (140°F) were evaluated. All materials exhibited satisfactory ozone resistance. No cracking or other visible defects were noted after any of the three tests.

Table 16. Rain Erosion Evaluation of Films and Coatings (0.7-mm-Diameter Drop Size)

Bonded Films					
Concept	Film	Thickness mm (mils)	Adhesive	Time to failure (min)	
				Specimen 1	Specimen 2
I	Kapton	0.13 (5)	PR 1422	2.5	3
II	Hytrel	0.25 (10)	PR 1422	15	42
III	Tradlon	0.13 (5)	PR 1422	7	8
IV	Hytrel	0.13 (5)	DP 6298	4.5	5
V	Tradlon	0.13 (5)	DP 6298	3	3
VI	Hituff	0.13 (5)	DP 6298	23	53
VII	Hituff	0.13 (5)	7064	10	35
VIII	UHMW Olefin	0.13 (5)	Adhesive- backed (acrylic)	8	8
IX	Kapton	0.13 (5)	56065	0.75	0.75
XI	Kynar	0.13 (5)	DA 552-1	2	2
XII	Kynar	0.08 (3)	Adhesive 80	2	2
XIV	Polyurethane (3M8562)	0.13 (5)	Adhesive- backed (acrylic)	25	25
XV	Polyester (3M5690)	0.08 (3)	Adhesive- backed (acrylic)	0.75	0.75
XVI	Kapton	0.13 (5)	Adhesive- backed (acrylic)	2	2
XVII	Kapton	0.13 (5)	Adhesive- backed (acrylic)	4	2.5
Sprayed Coatings					
Concept	Coating	Thickness mm (mils)	Time to failure (min)		
			Specimen 1	Specimen 2	
21	CAAPCO B-274 polyurethane*	0.30 (12)	517	437	
22	CAAPCO experimental polyurethane	0.30 (12)	135	110	
24	CAAPCO type II fluoroelastomer	0.30 (12)	20	28	
26	Astrocoat polyurethane (MIL-C-83231)	0.30 (12)	100	150	
27	BMS 10-60 polyurethane	0.30 (12)	11.5	—	
28	Hughson M313 polyurethane	0.30 (12)	199	200	
29	Dapcoat 3400 CS silicone	0.30 (12)	3.5	5	

*Two additional tests were conducted on CAAPCO B-274 with failure times of 257 min and 398 min.

Table 17. Rain Erosion Evaluation of Sprayed Coatings After 21-Day Weatherometer Exposure

Concept	Coating	Thickness mm (mils)	Time to failure (min)	
			Specimen 1	Specimen 2
21	CAAPCO B-274 polyurethane	0.30 (12)	210	> 600
24	CAAPCO Type II fluoroelastomer	0.30 (12)	22	18
26	Astrocoat polyurethane (MIL-C-83231)	0.30 (12)	94	94
28	Hughson M313 polyurethane	0.30 (12)	70	101

4.3.2.13 P-Static Noise Testing

An evaluation was made of the capability of selected coating materials to resist static charge buildup. These were precautionary tests conducted to ensure that flight performance of the 727 would not be degraded by the installation of the test panels (see sec. 4.3.4, which describes the flight service evaluation).

Eight panels were prepared for test and evaluation. Materials were bonded or sprayed onto 0.46m x 0.46m (18 x 18 in) 2024-T3 aluminum panels that had been surface cleaned with Scotchbrite and Alkanox and then alodined as described in appendix D. The aluminum panels were then primed with approximately 1 mil of MIL-P-23377 primer. Materials listed in table 18 were applied to the cleaned and primed panels.

Table 18. P-Static Test Panels

Concept	Coating material	Coating thickness mm (mils)	Adhesive material	Adhesive thickness mm (mils)	Application method
21-AS	CAAPCO B-274 with conductive topcoat	0.30 (12)	None	N/A	Spray
21	CAAPCO B-274	0.03 (1)	None	N/A	Spray
26	Astrocoat	0.30 (12)	None	N/A	Spray
28	Hughson M313	0.30 (12)	None	N/A	Spray
I	Kapton	0.13 (5)	PR 1422	0.13 (5)	Adhesive bond
III	Tradlon	0.13 (5)	PR 1422	0.13 (5)	Adhesive bond
VIII	UHMW polyolefin	0.13 (5)	Silicone adhesive-backed	0.03 (1)	Adhesive bond
XII	Kynar	0.13 (5)	Adhesive 80	0.13 (5)	Adhesive bond

Test procedures and results are reported in appendix E. The conclusions were that concept 21 (CAAPCO B-274), concept 26 (Astrocoat), and concept 28 (Hughson M313) were least susceptible to P-static noise generation under the condition of test. The remainder of the specimens evaluated were considered potential P-static noise and spark sources.

4.3.2.14 Advanced Testing Conclusions

Based on the studies conducted to date, three material concepts were selected as meriting further evaluation. The concepts are:

- Concept 21 (CAAPCO B-274)
- Concept 26 (Astrocoat)
- Concept 28 (Hughson M313)

The selection of these materials was based upon (a) processing and application characteristics, (b) rain erosion performance, (c) P-static noise testing, and (d) the environmental test results.

- a. **Processing and Application** – A satisfactory process has been developed for application of each of these three coatings. The process involves surface cleaning, priming, and spray application of the liquid coatings. Satisfactory adhesion has been demonstrated throughout the program using this basic process. It should be noted that the film application process requires additional development work, particularly in the area of adhesive selection. Adhesive selection is highly dependent upon the particular film to be bonded. Schedule constraints of this program did not permit a thorough study of film adhesives.
- b. **Rain Erosion Performance** – The CAAPCO B-274 and Hughson M313 coatings exhibited the highest rain erosion resistance of the materials evaluated. Astrocoat is considered a current industry standard rain erosion coating, and is qualified to MIL-C-83231. In addition all three of these materials exhibited satisfactory rain erosion performance following weatherometer exposure.
- c. **P-Static Noise Testing** – CAAPCO B-274, Hughson M313, and Astrocoat were found from test to be the least susceptible to P-static noise generation of the eight materials evaluated. The remaining materials were considered to be potential P-static noise sources. Details of this evaluation are included in appendix E.
- d. **Environmental Tests** – The three polyurethane coatings selected for further evaluation, CAAPCO B-274, Hughson Chemglaze M313 and Astrocoat, exhibited satisfactory performance in all environments except extended immersion in synthetic type hydraulic fluid. However, when the coatings are applied to leading edges for erosion protection, this degree of exposure to hydraulic fluid would not be expected. Further investigations should be pursued to determine the extent of hydraulic fluid exposure that can be tolerated by these materials, and/or what preventive maintenance practices should be followed.

The behavior of coating materials in icing conditions was not investigated during the program. Although jet transports infrequently experience icing, the affinity for or rejection of ice, and the durability of coatings in icing conditions should be examined.

4.3.3 Estimated Service Life

A prediction of service life of an erosion coating applied to the leading edge of a wing was made for the coating with the best erosion performance in the whirling arm tests. This was the CAAPCO B-274 coating currently undergoing MIL-C-83236 qualification. This material (in 12-mil thickness) survived for 16 min before the onset of damage when subjected to a 2-mm drop size. These data were used to derive effective fatigue strength of the coating for use in the prediction model described in the subsequent discussion. The test condition is severe compared to the flight environment defined in section 4.1, particularly with respect to the large drop size (2 mm compared to 0.7-1.0 mm). The same material, in a whirling arm test with an average drop size of 0.7 mm, survived in excess of 400 min without discernable damage. As will be shown, these results are consistent with the model predictions.

The typical daily operation profile for a medium-range transport, defined in section 4.1 (see fig. 3), shows three flights per day with a total daily block time of 7.06 hr. In addition, it was projected that rain corresponding to 2.54 cm (1 in) per hr at ground level would be encountered during one of the three daily flights. At 1524m (5000 ft) altitude and below, the rain was characterized as 1000 drops per m³, with a 1-mm drop size. Above 1524m (5000 ft) altitude, the rain was defined as 2000 drops per m³, with a 0.7-mm drop size. No rain would be encountered above 7620m (25,000 ft) altitude. These environmental conditions are repeated in table 19 in the format used in the prediction model. Results of the prediction indicate that the coating should survive the target 5000-hr operation with a 15% margin on coating life. It should be recognized that this prediction is based on rain erosion performance only, and considers no performance degradation that might result from exposure to other environmental factors.

Table 19. Predicted Service Life for Best Erosion Coating (CAAPCO B-274)

Flight condition	Drop density m ⁻³	Drop size mm	Velocity m/s	Knots equivalent airspeed	Time in rain* hr	Fraction of life expectancy
Climb (sea level to 5000 ft)	1000	1.0	175	340 at sea level	40	0.2
Climb (5000 - 10 000 ft)	2000	0.7	188	340 at 5000 ft	40	0.065
Climb (10 000 - 15 000 ft)	2000	0.7	204	340 at 10 000 ft	37	0.10
Climb (15 000 - 20 000 ft)	2000	0.7	240	340 at 20 000 ft	37	0.31
Descent (20 000 - 15 000 ft)	2000	0.7	197	280 at 10 000 ft	32	0.012
Descent (15 000 - 10 000 ft)	2000	0.7	166	280 at 10 000 ft	32	0.07
Descent (10 000 - 5000 ft)	2000	0.7	155	280 at 5000 ft	46	0.021
Descent (5000 to sea level)	1000	1.0	144	280 at sea level	46	0.06
Total					310	0.85

*Time in rain based on 5000 flight hours

Conclusion: Predicted survival is $5000/0.85 = 5880$ hr

In table 19, it is noted that the most severe erosion environment occurs at 175 m/s (340 keas) at 6096m (20000 ft) altitude, where 37 hr in rain expends 31% of the useful life of the coating. Transports operating in many parts of the world probably are not exposed to this severe rain environment; consequently, their coating service lives should be extended considerably.

4.3.3.1 Analytical Method for Estimating Service Life

Materials exposed to a steady rain environment typically exhibit an initial time period in which no apparent damage occurs. Following this initial incubation period, the end of which may be marked by surface damage such as pitting or cracking, a second period of progressive damage marked by a relatively constant mass loss rate occurs. For application to the leading edge of a wing, the criterion for coating performance is the onset of surface roughening.

An analytical model based on fatigue concepts has been developed by Springer (ref. 7), which predicts the number of impacts required to initiate surface damage. The model predicts the effects of raindrop diameter, velocity, coating thickness, and coating structural properties on the number of impacts to failure. This is readily extended to a prediction of coating life in a given rain environment. The model characterizes erosion coating materials by the following properties:

- Acoustic impedance (product of density and sound speed)
- Poisson's Ratio
- Tensile strength
- Endurance limit
- Characteristic slope of the S-log N (fatigue) curve

The model accounts for the effects of stress wave reflections in the coating that result in magnification of the impact stress levels, and the number of cycles above those encountered by a simple impact on a thick homogeneous material. It also accounts for stresses imparted by droplet impact at varying radial distances from the reference location.

Fatigue strength of the coating material is characterized by a parameter of the form:

$$S_c = \frac{4 \delta u (b-1)}{(1 - 2 \nu)} \quad (\text{equation 1})$$

S_c = Effective fatigue strength of coating

δu = Ultimate tensile strength of coating

b = Slope of S-log N fatigue curve

ν = Poisson's Ratio

The number of impacts per unit area required to initiate surface damage is:

$$N_i = \frac{8.9}{d^2} \left(\frac{S_c}{\delta_c} \right)^{5.7} \quad (\text{equation 2})$$

N_i = Number of impacts per m^2

d = Drop size, mm

S_c = Effective fatigue strength of coating

δ_c = Average stress in coating during impact

where the numerical constants have been empirically determined from rotating arm data on a wide variety of materials.

The initial stress in the coating before any wave reflection effects is equal to the impact pressure. This is computed by considering a one-dimensional impact between a water droplet and the coating. The pressure at the impacted surfaces is obtained from basic hydrodynamic theory, considering the equations of continuity of mass and momentum across a normal shock. The resulting equation for the impact pressure normal to the surface is:

$$P = \frac{Z_w V}{1 + \frac{Z_w}{Z_c}} \quad (\text{equation 3})$$

P = Impact pressure

Z_w = Acoustic impedance of droplet

Z_c = Acoustic impedance of coating

V = Impact velocity normal to surface

For thin coatings typical of those under consideration, the coating stress is magnified to levels higher than the impact pressure because of the interaction of shock reflections in the coating during the time period of the impact. Thus, thin coatings in which shock reflections are significant are predicted to have surface failure initiated at shorter times than do thick coatings, because of their higher coating average stress. A single stress reflection from a hard substrate such as aluminum alloy nearly doubles the stress level in a soft erosion coating.

The treatment of stress intensification by wave reflection in thin coatings is handled by considering one-dimensional stress wave propagation in elastic materials. This is a simplification to make the analysis tractable, but small errors in the coating stress prediction mass result in large errors in predicted incubation time because of the sensitivity introduced by the exponent in equation 2. Further, the best erosion coatings are elastomeric in nature, rather than elastic.

Several weaknesses in the model are apparent from examination of the constants in the above equations, developed from the available data. The slope, b , of the S-log N curve was assumed to be constant for all materials. The value used by Springer, $b = 20.9$, is typical of metals. Very little data are available to support the use of this value for plastics. The constants in equation 2 are developed from a best fit of data for a wide range of materials. However, data for each material are limited to a relatively narrow range of S_c/δ_c , with the exponent determined by assuming it is independent of type of material. The very high value of the exponent (5.7) makes the predicted incubation times very sensitive to small variations in either the material strength parameter or the coating stress. Since both of these quantities may be subject to considerable uncertainty, prediction of coating life from basic material properties is questionable.

The model is useful for the design of experiments because the relative importance of experimental parameters is highlighted. Drop size, velocity, and coating thickness effects might be expected to be reliably correlated from data on a given material. Unfortunately, available data do not exercise the parameters sufficiently to adequately test the model, since most experiments to date have been designed for a relative comparison of material performance in a standardized environment. Most of the data available to substantiate the model are for drop sizes of $1\frac{1}{2}$ to 2 mm and impact velocities of 224 to 268 m/s (500 to 600 mi/hr). The theory has not been adequately tested for smaller drop sizes and the lower velocities (e.g., climb and descent), during which most of the rain is encountered in airline operation.

An example of the drop size and the impact velocity effects predicted by the model is illustrated in table 20. The material is CAAPCO B-274 polyurethane with an effective fatigue strength derived from 224 m/s (500 mi/hr) whirling arm test at 2.54 cm (1 in) per hr rainfall with 2-mm drop size. Using the measured survival time of 16 min (0.27 hr) as baseline, the Springer model predicts a survival time of 5.6 hr if the drop size were 1.0 mm, and 17.6 hr if the drop size were 0.7 mm. In an actual test with an average drop size of 0.7 mm, the observed incubation time was 6 to 8 hr; substantially less than the 17.6 hr predicted. However, at this test condition the drop size range approximates a normal distribution with many drops as large as 1.0 mm and a few as large as 1.5 mm. Considering the effect of those droplets, which are larger than average size, brings the predicted incubation times into the range actually observed. (The size distribution for the 2 mm droplet test was very narrow—all the droplets were very nearly uniform).

The effect of using a lower test velocity that is closer to the climb and descent flight environments is also illustrated in table 20. The predicted incubation times at 179 m/s (400 mi/hr) are $4\frac{1}{2}$ times the corresponding times at 224 m/s (500 mi/hr). For a 2-mm drop size at 179 m/s (400 mi/hr), the predicted incubation time is 1.2 hr. It would appear highly desirable to perform an experiment at this condition to verify the prediction model. (This would require a modification of the Avco rain erosion facility to obtain the lower velocity.)

Table 20. Correlation of Prediction* and Test—Rain Erosion Life

- 12-mil polyurethane coating
- Rain rate = 2.54 cm (1 in/hr)
- Avco test facility

Drop size mm	Velocity m/s (mph)	Coating stress kN (kpsi)	Impacts to roughen cm ⁻²	Impact rate cm ⁻² /min ⁻¹	Predicted time to roughen hr	Test time to roughen hr
2.5	224 (500)	67.6 (15.2)	2,518	542	0.08	0.27 6 to 8
2.0	224 (500)	61.8 (13.9)	17,000	1,055	0.27	
1.0	224 (500)	48.5 (10.9)	3.1 x 10 ⁶	9,200	5.6	
0.7	224 (500)	44.0 (9.9)	31 x 10 ⁶	29,400	17.6	
2.5	179 (400)	54.3 (12.2)	3,950	434	0.15	
2.0	179 (400)	49.8 (11.2)	140,000	844	1.2	
1.0	179 (400)	38.7 (8.7)	28 x 10 ⁶	7,370	25.1	
0.7	179 (400)	35.1 (7.9)	110 x 10 ⁶	235,000	77.9	

*By Springer's method

4.3.3.2 Analytical Results

Results of the prediction, included in table 19, indicate that the coating should survive the target 5000-hr operation with a 15% margin on coating life. These results are based upon an airplane encountering rain one-third of the time during climb and one-third of the time during descent. Less frequent rain encounter will result in proportionally longer coating lives. It should be recognized that this prediction is based on rain erosion performances only, and considers no performance degradation that might result from exposure to other aircraft environments.

In table 19, it is noted that the most severe erosion environment occurs at 175 m/s (340 keas) at 6.1 km (20 000 ft) altitude, where 37 hr in rain expends 31% of the useful life of the coating. In view of the severity of this particular environment, the reality of encountering the amount of rain assumed at 6.1 km (20 000 ft) should be critically examined.

4.3.4 Flight Service Evaluation

A flight service evaluation of the two final candidate materials that exhibited the best rain erosion characteristics was initiated at the conclusion of the study. In September 1978, Continental Airlines applied CAAPCO B-274 and Chemglaze M313 to the leading edges of wing and horizontal tail surfaces of a 727. The test configuration is shown in figure 8. The airplane is in the service of Air Micronesia in the Pacific arena, and operates in a severe erosion environment. Airline and contractor field personnel will monitor the condition of the surface coatings on a periodic basis and report to the Contractor. At this writing (2 months in evaluation) no change in the condition of the coatings had been observed.

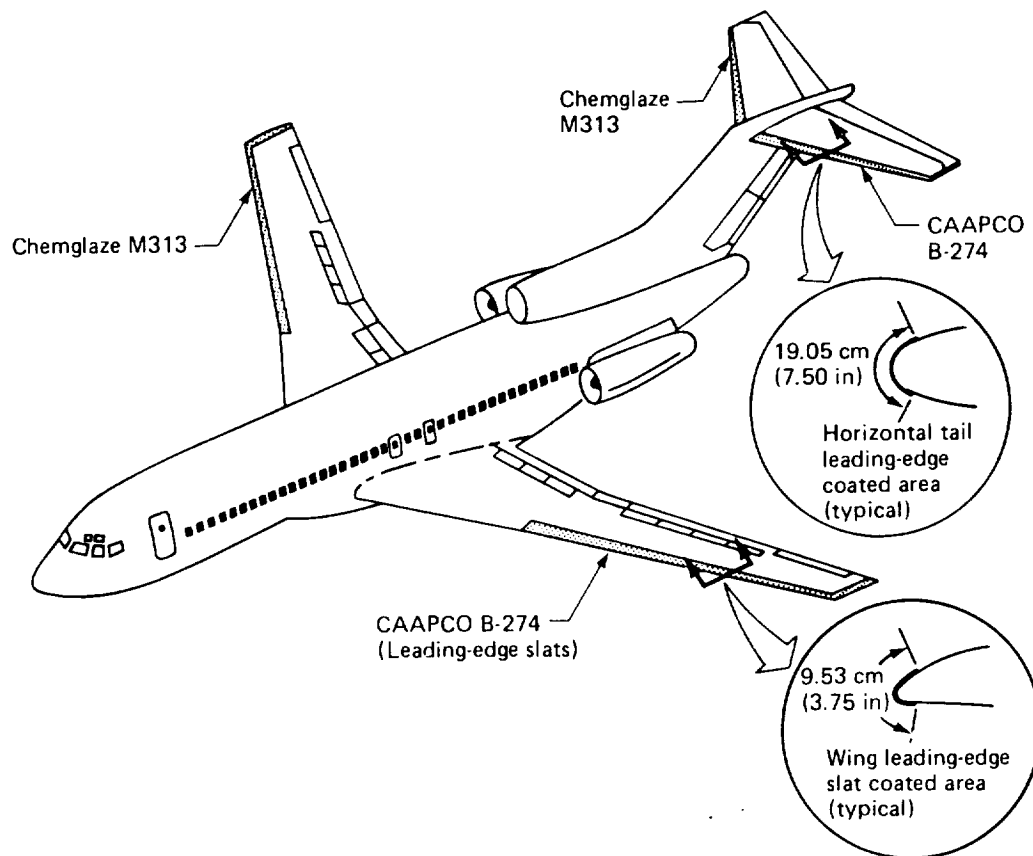


Figure 8. Coated Areas—Flight Service Evaluation

The coatings were applied to the 727 leading-edge areas, as shown in figure 8, by airline maintenance personnel per instructions from the Contractor. The initial application was on all of the surfaces except slats 2 and 7 (refer to fig. 9—second slats inboard from left and right wingtips). Some edge tearing of the CAAPCO B-274 coating was experienced when the masking tape was removed. Slats 2 and 7 were coated a few days later, and the application procedure was modified to overcome the tearing problem. Thus, the flight service evaluation will provide valuable data on large-scale field application and repair, as well as an evaluation of durability in a severe airline operating environment. The evaluation will continue until the erosion resistance characteristics of the two coating materials have been determined.

4.3.5 Repair Procedures

Development of repair procedures for the selected concepts can only be postulated at this time, based on laboratory testing of small-scale specimens. The repair of coating systems should be relatively straightforward; however, procedures for repairing film systems will most likely depend on the nature and extent of damage. Experience and experiments with large-scale film applications are needed to develop valid repair procedures for these concepts.

4.3.5.1 Coating Repair Procedures

The coatings selected (concepts 21, 26, and 28) are polyurethane sprayed coatings. They have excellent adhesion to aluminum substrate precoated with MIL-P-23377 or BMS 10-79 primer systems. Normal deterioration of the coating will not result in the peeling or tearing that would result in large areas of exposed surface. Incipient failure will be first indicated by a dulling of the coating surface. This will be followed by roughening and pitting. Preventive maintenance, in the form of a thin coating of polyurethane, will restore the dull coating by resealing the surface.

In the case of areas in more advanced stages of deterioration, the coating probably should be completely removed in the affected area, followed by reapplication of several spray coats of the polyurethane material to build up the coating to the desired thickness. This procedure also would apply to areas receiving foreign object damage (FOD).

4.3.5.2 Film Repair Procedures

Film damage probably would occur in one of two forms; scuffing of the surface, or debonding of the film from the substrate followed by tearing/peeling. It is possible that localized scuffing due to FOD could be repaired by applying a thin coating of adhesive over the damaged areas, followed by careful smoothing prior to curing. In the case of torn/peeled film, the probable repair procedure would involve removal of adjacent areas of film back to where the film/substrate bond is unaffected, and inlaying a patch of film of the exact size and shape. Much care would be required to ensure that the film butt joints were faired and sealed to prevent recurrence of the failure. As stated earlier, a well-defined repair procedure must be preceded by large-scale film application research.

4.3.6 State of Art Weaknesses

4.3.6.1 Bonded Films

The optimization of surface preparation techniques and the selection of primers and adhesives that provide both acceptable strength and environmental resistance characteristics are complex tasks. The current program investigated seven generic classes of film material, with a minimum of two adhesive materials per film. It became apparent, however, that a much more extensive adhesive study was necessary to achieve acceptable bond strengths, particularly after exposure to environmental testing. Only one of the film classes (polyester) was found clearly unacceptable in the environmental evaluations. Most of the deficiencies were related to adhesive selection and surface preparation of both films and substrates.

Maximum size of bonded film specimens fabricated was several square feet. Even at this relatively small size, it was apparent that adhesive candidates involving even moderate quantities of volatile material on curing resulted in unacceptable debond and blistering of the film. Most of the adhesive materials had severe deficiencies in one or more of the environmental exposures. Considerable additional laboratory process development is necessary before large-scale application of adhesively bonded films is attempted on flight hardware.

The Contractor has extensive experience in producing panels covered with protective films for passenger cabins of commercial transports. Although these sidewall panels are of moderate size, the process for acquiring a smooth surface with a high-quality bond required considerable research. The bonding of films to the panels, which include areas of deep forming and compound curvature, is accomplished by using a cast film that is preformed to contour with heated dies. The film is then bonded to the substrate with a matching die caulplate to produce a smooth surface. Pressure and heat are applied to the caulplate during the adhesive curing process. If this procedure were used to apply a film to the entire surface area of a transport wing, the difficulties and cost would be prohibitive.

Study results indicate that the potential benefits from films relate primarily to their ability to provide aerodynamically smooth surfaces over large areas, such as wing and empennage inspar areas, rather than from erosion protection of leading edges. Smooth surfaces require that excrescences in the substrate be eliminated or effectively masked before film layup. Present methods of substrate preparation for smoothness are costly, and involve special design and manufacturing procedures.

The problem of precipitation-static charge dissipation from film surfaces also requires critical evaluation and development of appropriate corrective techniques. All four films evaluated in P-static tests on this program (Tradlon, Kapton, Kyner, and UHMW polyolefin) exhibited characteristics that would limit the film application to areas of low exposure to P-static buildup. Results of the P-static tests are included as Appendix E. Either the development of new design techniques or modifications of film electrical characteristics may be required.

4.3.6.2 Sprayed Coatings

Polyurethane elastomers for rain erosion protection of radomes and metallic leading edges have been used effectively for many years. However, analytical predictions of service life using the prediction model have not been adequately verified for accuracy at the relatively low climb and descent velocities and rain environments of interest. Laboratory evaluation of the best erosion coatings in the simulated commercial environment may not be practical, because of the long test times required and the many variables that should be investigated.

The polyurethane coatings are subject to significant degradation by the synthetic hydraulic fluid used in commercial airliners. Critical assessment of this problem and exploration of potential solutions should be pursued.

4.3.7 Development Recommendations

4.3.7.1 Laboratory Process Development

Further process development work is required, particularly for the bonded film applications. Selection of candidate film materials should be limited to a workable number, and an extensive evaluation of the process variables should be performed. The following tasks are recommended:

- Develop substrate preparation requirements
- Investigate characteristics of primers and adhesives relative to curing and thickness requirements, to produce satisfactory bond strength in the operating environment
- Define application process requirements for selected adhesive-bonded film systems. Evaluate various tooling concepts in the laboratory and extrapolate to full-scale conditions. Assess feasibility of selected concepts for factory and airline inservice applications
- Evaluate and establish procedures for maintenance, repair, removal, and replacement of surface coatings

4.3.7.2 Large-Scale Applications Evaluation

Development of full-scale applications of both film/adhesive and sprayed coating candidates should be pursued. Although the bonded film systems require further process development, as defined in the previous section, development of tooling requirements for films and adhesive application can be performed concurrently. For the sprayed polyurethane erosion coatings, the current state of process development should permit immediate initiation of large-scale application. The following tests are recommended:

- Using full-scale hardware (e.g., wing section, wing glove, horizontal tail), demonstrate and verify the procedures established for substrate preparation, primer/adhesive application, and film coating application. Verify the capability of the selected tooling system to produce surface finishes within required tolerances
- Demonstrate, on full-scale hardware, the procedures established for maintenance, repair, and removal and replacement of local and major areas of the surface coating
- Investigate methods of determining coating bond integrity through nondestructive testing (NDT)
- Prepare specifications covering material application procedures and surface finishes

4.3.7.3 Performance Evaluation

The following tests are necessary to perform a valid cost/benefits analysis and to make recommendations relative to the application of films/coatings to transport aircraft:

- Conduct wind tunnel/flight testing of surface coating systems applied to large surfaces. Determine bonding durability, erosion resistance, and drag reduction compared to uncoated surface
- Perform rain erosion tests to investigate the critical test parameters (velocity, drop size, coating thickness, impact rate) in the range of commercial aircraft application for both coating evaluation and verification of analytical prediction techniques
- Contingent upon airline approval, install surface coating on major areas of wing/horizontal tail of inservice transports to determine the validity of system field installation procedures and system durability in the operating environment

4.4 COST/BENEFITS ANALYSIS

Based on results of the materials and process testing described in the preceding section, a cost/benefits analysis of CAAPCO B-274, Chemglaze, and Astrocoat was conducted. Film applications were not analyzed in detail, because the study did not produce a process whereby films could be applied successfully to the inspar region of wings. Film application costs, therefore, could not be evaluated. For reference, however, the drag benefits from films in the inspar area were estimated to be the same as for coatings. The cost/benefits analysis presented here stresses the increase or decrease in airplane operating cost resulting from the application of the various coatings. Of significant importance, also, is the potential fuel saving that could result from the application of drag-reducing coatings. These results are addressed in section 4.4.3, Benefits Analysis.

The methodology used in the cost/benefits analysis of coating materials consisted of (1) assessing the cost of labor, materials, and airplane on ground (AOG) time for the coating and for today's paint applications; (2) estimating the airplane drag reduction and weight increase resulting from the coating application; and (3) calculating benefits in terms of fuel saved and the difference between the cost of fuel saved and the increased cost of the coating application over that of today's paint application. All costs are expressed in 1978 dollars. The baseline airplane chosen for this analysis is the 727-200 operating under the following ground rules:

Fleet size	2000 airplanes
Utilization	2500 hours/year
Mission range	1611 km (870 nmi)
Block time	2.33 hr
Trips per day	3

Three cases of increasing coating coverage were examined, as defined in table 21 and illustrated in figure 9. Wing and empennage geometry of the 727 is defined in figure 10.

A current paint system chosen as the baseline has a primer (BMS 10-79, Type II) on the inspar (between front and rear spar) regions of wing and empennage, polyurethane enamel (BMS 10-60, Type II) on the inspar regions of the empennage and lower wing skin, and Corogard on the inspar region of the upper wing skin. The leading edges, back to the front spar, are unpainted. This system periodically requires a total field repaint, and, while their experience is quite varied, many airlines repaint during scheduled "D" maintenance checks. Thus, a repainting frequency of once every 15 000 flight-hours (which approximates the "D" check interval) was selected for this study. In addition, frequent buffing of leading edges is required because of rain erosion.

Table 21. Coating Application Areas

Area covered		
	Wing	Empennage
Case I	Slats, flaps, and leading edge (LE) to 5% chord on upper inboard surface	LE to 5% chord
Case II	LE to front spar	LE to front spar
Case III	LE to rear spar	LE to rear spar

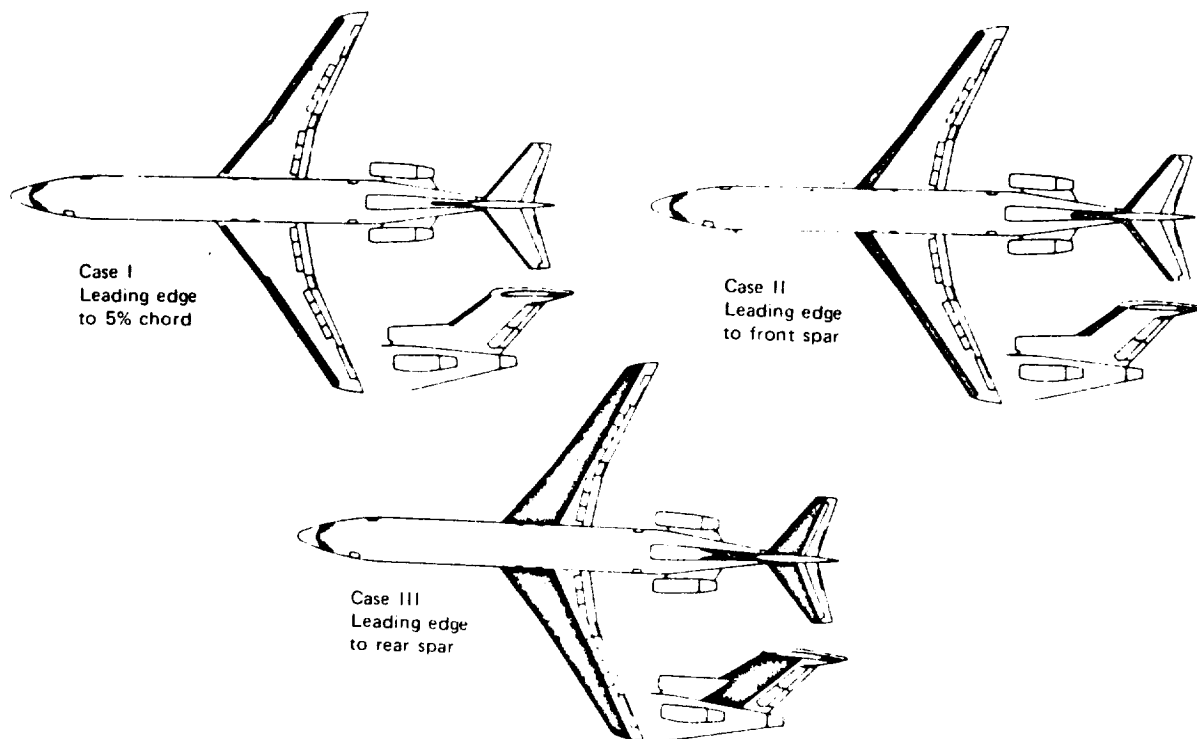


Figure 9. 727-200 Coating Application Areas

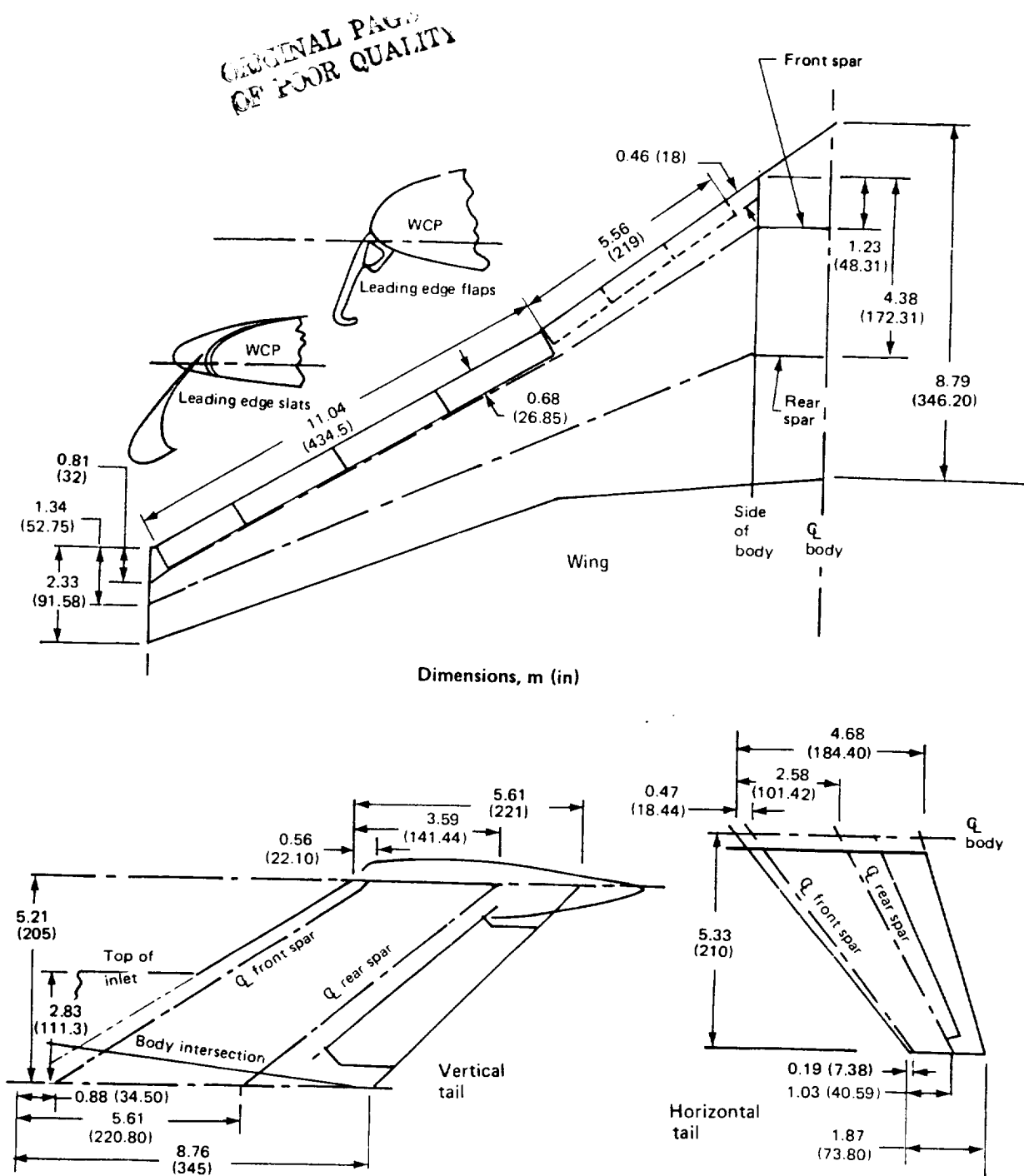


Figure 10. 727 Wing and Empennage Geometry

4.4.1 Application Costs

The data base for application costs was based on current inplant factory labor for painting Model 727-200 airplanes, together with the material costs of the candidate coatings and the differences in application labor and flow time. The final-painting of a Boeing 707, 727, or 737 usually is completed in 3 days, working two shifts.

In making application cost estimates, the present times required for initial airplane washing and final cleanup were used. The times required for application of each coat of primer and finish for the candidate coatings were also assumed to be the same as for the present paint system. Differences in total application times (flow times) for the coatings were a function of the different number of coats required, the different drying times required, and the size of the areas to be spray-coated. An estimate of flow times is contained in table 22. Table 23 offers a comparison of cost and weight characteristics of the various paint and coating system components. Tables 24 and 25 show the areas, weight, and material costs for the three application areas examined (cases I, II, and III).

4.4.2 Drag and Fuel Reduction

In the absence of test data, estimates of the potential drag reduction on a 727-200 were made for the three cases examined. Based on profilometer measurements of the coating surfaces (sec. 4.3.2), it was assumed that the coating application would eliminate wing and empennage roughness drag over the areas covered. Credit was taken for only part of the excrescence drag; e.g., skin joints and rivet rows. Excrescence drag caused by gaps between moving components, such as control surfaces or high-lift devices, would not be reduced by the application of a coating. (It is speculated that films, if they could be successfully applied to the inspar region, would reduce drag by the same amount as coatings.)

Table 26 shows the estimated roughness and excrescence drags associated with the 727-200 wing and empennage areas being considered for the three cases of coating application described in section 4.4. Drag coefficient of the untreated surfaces, as well as the estimated drag benefits of the coating applications, are shown. From this table, it is seen that the coating application can effect a drag reduction of up to 0.17% if only leading edges are treated (case I), and up to 1.62% if the area from the leading edge to rear spar is treated (case III). These percentages are based on the total airplane drag coefficient of 0.0290 at cruise conditions ($C_L=0.43$ and $M=0.80$).

Whether a particular coating can achieve all or part of this potential reduction in roughness and excrescence drag can be determined only by a detailed analysis, followed by test verification. These activities were beyond the scope of this study. However, it is believed that the values represent a reasonable upper limit of the drag benefits of coating/film applications.

The sensitivity of 727-200 mission fuel burned to increments in drag and operating empty weight (OEW) is shown in figure 11. The following equation, derived from the Brequet range equation for 727 long-range cruise conditions, represents this sensitivity as a linear relationship, and therefore is valid only for small changes in drag/weight.

Table 22. Coating Application Time Estimates

	Case I		Case II		Case III	
	Direct labor, hr	Flow time, hr	Direct labor, hr	Flow time, hr	Direct labor, hr	Flow time, hr
<u>Painting:</u>	①	①	①	①		
Prepare, clean, and mask					16	4
Prime					16	4
Cure primer						1
Paint					16	4
Cleanup					8	2
Postcure						48
Total					56	63
<u>Coating:</u>						
Prepare, clean, and mask	16	4	16	4	16	4
Prime	5	4	8	4	24	4
Cure primer		12/1/2 ②		12/1/2 ②		12/1/2 ②
Paint:						
Astrocoat	30	36	48	36	144	36
CAAPCO B-274	26	25	42	25	126	25
Chemglaze M-313	10	14	16	14	48	14
Cleanup	8	2	8	2	8	2
Postcure (accelerated)		48		48		48
Total:						
Astrocoat	59	106	80	106	192	106
CAAPCO	55	84	74	84	174	84
Chemglaze	39	74	48	74	96	74
<u>Time differential</u> (coating-painting)						
Astrocoat	59	106	80	106	136	43
CAAPCO	55	84	74	84	118	21
Chemglaze	39	74	48	74	40	11

① Paint not applied to Cases I and II areas on Baseline 727-200

② 12, 1, and 2 hours for Astrocoat, CAAPCO, and Chemglaze, respectively

Table 23. Material Characteristics

	Cost, \$/m ³ (\$/gal)	Applied weight, kg/m ² (lb/ft ²)	Coverage, m ³ /m ² (gal/ft ²)	Cost, \$/m ² (\$/ft ²)
Astrocoat	21 134 (80)	0.293 (0.06)	0.0012 (0.03)	25.83 (2.4)
CAAPCO B-274	18 492 (70)	0.293 (0.06)	0.0012 (0.03)	22.60 (2.10)
Chemglaze M-313	4227 (16)	0.293 (0.06)	0.0012 (0.03)	5.17 (0.48)
Primer	7397 (28)	0.029 (0.006)	0.0004 (0.01)	3.01 (0.28)
Corogard	7133 (27)	0.085 (0.0175)	0.0003 (0.0083)	2.41 (0.224)
Polyurethane enamel	7397 (28)	0.029 (0.006)	0.0010 (0.025)	7.53 (0.70)

Table 24. Painting/Coating Areas and Weights of Applied Materials

	Case I		Case II		Case III	
	Area, m ² (ft ²)	Weight, kg (lb)	Area, m ² (ft ²)	Weight, kg (lb)	Area, m ² (ft ²)	Weight kg (lb)
Painting:	*	*	*	*		
Primer					174.38 (1877)	5.11 (11.26)
Corogard					55.00 (592)	4.70 (10.36)
Polyurethane enamel					119.38 (1285)	3.50 (7.71)
Total						13.31 (29.34)
Coating:						
Primer	36.23 (390)	1.06 (2.34)	65.31 (703)	1.91 (4.22)	239.69 (2580)	7.02 (15.48)
Coating	36.23 (390)	10.61 (23.40)	65.31 (703)	19.13 (42.18)	239.69 (2580)	70.22 (154.80)
Total		11.67 (25.74)		21.04 (46.40)		77.24 (170.28)
Weight differential (coating-painting)		11.67 (25.74)		21.04 (46.40)		63.93 (140.94)

*Paint not applied to Cases I and II areas on Baseline 727-200

Table 25. Material Costs

	Case I			Case II			Case III		
	Component cost, \$	Total cost, \$	Material cost difference coat-paint, \$	Component cost, \$	Total cost, \$	Material cost difference coat-paint, \$	Component cost, \$	Total cost, \$	Material cost difference coat-paint, \$
Painting:									
Primer	—			—			526		
Corogard	—			—			133		
Polyurethane enamel	—	—		—	—		899	1558	
Coating:									
Primer	109			197			722		
Coating									
Astrocoat	936	1045	1045	1687	1884	1884	6192	6914	5356
CAAPCO	819	928	928	1476	1673	1673	5418	6140	4582
Chemglaze	188	297	297	339	536	536	1244	1966	438

Table 26. Potential Drag Reduction Benefits

Airplane element	Drag type	Estimate of drag coefficient, C_D			
		Baseline 727-200 without coating/film	727-200 with coating/film		
			Case I	Case II	Case III
Wing	Excrescence	0.00075	0.00075	0.00075	0.00057
	Roughness	0.00015	0.00012	0.00009	0
Horizontal tail	Excrescence	0.00011	0.00011	0.00011	0.00008
	Roughness	0.00004	0.00003	0.00002	0
Vertical tail	Excrescence	0.00010	0.00010	0.00010	0.00007
	Roughness	0.00004	0.00003	0.00002	0
Wing and empennage	Total	0.00119	0.00114	0.00109	0.00072
Total reduction in C_D		—	0.00005	0.00010	0.00047
Percent reduction in airplane C_D		—	0.172	0.345	1.621

$$\text{Fuel savings} = 86.7692(\Delta C_D) - 0.16(\Delta \text{OEW}),$$

where:

Fuel savings is in $\text{m}^3/\text{airplane}/\text{year}$

ΔC_D = reduction in airplane coefficient of drag in %

ΔOEW = increase in OEW in kg

As an example, if 50 kg (110 lb) of coating could reduce the total airplane drag by 1%, the savings would be about 78.77 m^3 (20 809 gal) of fuel per airplane per year. A typical landing weight of 58 967 kg (130 000 lb) was selected corresponding to a load factor of about 60%, with ATA domestic reserves and a typical OEW. A utilization of 2500 hr per year and a 1611 km (870 nmi) range mission, with block time of 2.33 hr, were assumed. The brake release gross weight required for this mission was allowed to vary to accommodate changes in mission fuel required and OEW.

4.4.3 Benefits Analysis

In order to smooth out discrete costs that occur at different accumulated operating hours for the paint and coating applications, a long (45 000 hr) flight-hour cycle was analyzed, and the costs were reduced to average annual costs. During the 45 000-hr cycle, one factory application, two field repainting or recoating applications, and several leading-edge repairs would be experienced. For each of these applications or repairs, the following costs were assessed: labor costs based on hr in table 22 and a fully burdened rate of \$31.50 per direct manhour; material costs taken from table 25; and airplane on ground (AOG) costs (based on estimates from ref. 8) of \$387 per lost flight-hour, which corresponds to \$113 per downtime hr based on a 7-hr per day utilization. The downtimes are taken from table 22.

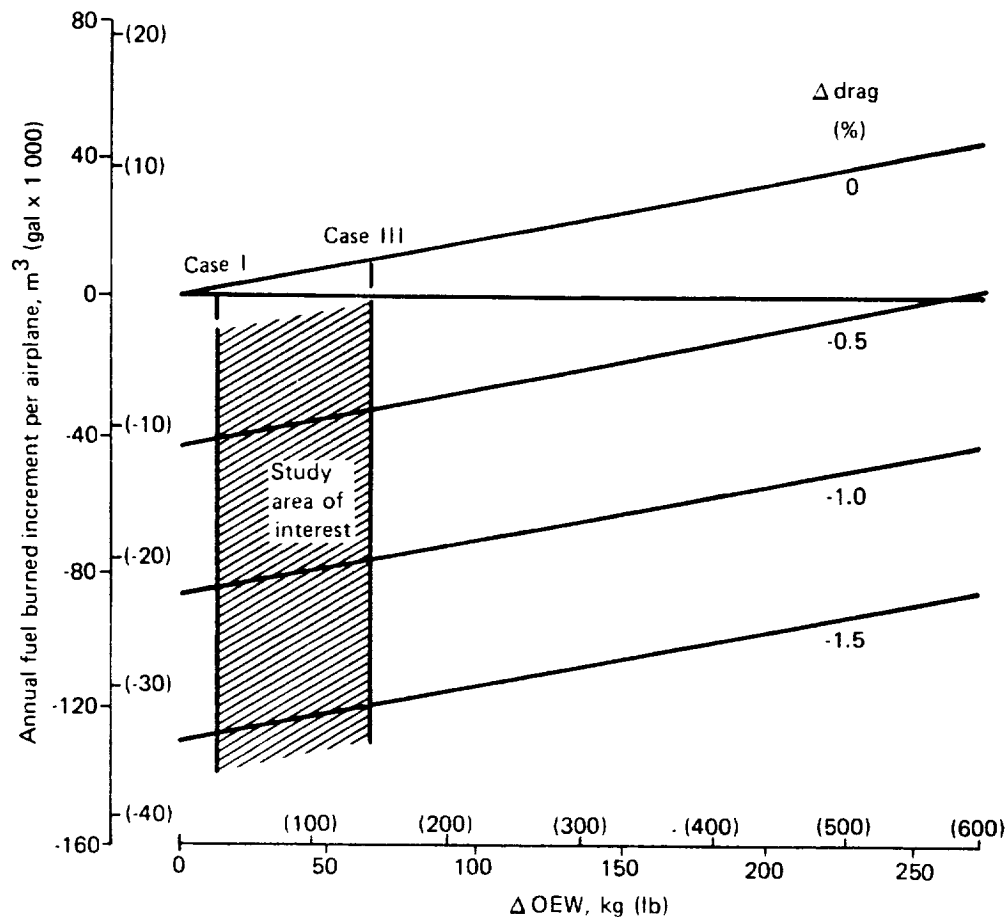


Figure 11. Fuel Burn Sensitivity to Weight and Drag

The factory application consists of painting the inspar regions or coating the case I, II, or III areas. The AOG costs were not charged for this initial application. In the field, it was assumed from limited airline data that the areas analyzed would require repainting or recoating during scheduled "D" maintenance checks (about every 15 000 hr), thus two total repaint/recoat processes are encountered during the 45 000-hr cycle. This requires stripping the old paint or coating, requiring about 1 man-hour per 4.18 m² (45 ft²). For cases I and II, no AOG cost charge was applied for the field recoat, since the leading edges can be removed from the maintenance site and recoated concurrently with the maintenance check within normal flow time. For case III, however, an AOG cost was charged, because repainting or recoating the inspar region would interfere with the maintenance activity, and must be accomplished after the normal maintenance check.

Additionally, the leading edges must be maintained periodically because of erosion. In the case of the painted system (bare leading edges to front spar), this requires about 4 man-hours of buffing every 2500 flight-hours. Since this process would be accomplished during scheduled maintenance checks, no AOG costs were charged. For the coating applications, the frequency of such repair was based on rain erosion tests discussed in section 4.3 and summarized in table 27.

Table 27. Rain Erosion Test Results

Material	Survival time (min)	Equivalent* flight-hours
CAAPCO B-274	430	6000
Chemglaze M313	200	2790
Astrocoat	125	1745

*Based on rain encountered every third flight during climb and descent.

Thus, the replacement time for the leading-edge areas would be 6000, 2790, and 1745 hr for CAAPCO, Chemglaze, and Astrocoat, respectively. The AOG costs were charged for this maintenance, because of the long postcure times involved. The number of applications, hr, and costs for the paint and coating materials for the 18-year, 45 000-hr cycle are contained in table 28. The differential costs between the coating and painting applications were reduced to annual costs to be compared to the benefits from reduced fuel burn. It should be noted that the largest single factor contributing to coating costs is AOG time.

The estimated potential dollar benefits of applying a coating material in lieu of today's paint application to reduce airplane drag and save fuel are summarized in figure 12 for cases I, II, and III. The ordinate scale in figure 12 represents the estimated dollar savings in fuel from coating compared to painting, minus the difference in their application and maintenance costs.

The benefits are shown as a percent of the total potential drag reduction taken from table 26. The benefits are predicated on fuel prices of 106, 159, and \$211/m³ (40, 60 and 80¢/gal), the lower figure approximating today's domestic fuel price. From these figures, it is apparent that only case III coverage would show promise. At current fuel prices, CAAPCO B-274 shows a break-even if only 40% of the potential drag reduction is realized, Chemglaze at 60%, and Astrocoat not at all. Astrocoat shows a break-even only at the \$211/m³ (80¢/gal) fuel price and 80% drag reduction. Combination coatings, such as CAAPCO on the leading edge and Chemglaze on the inspar region, were not considered for case III, because differences in material costs were small compared to total application costs. Also, the added complexity of a two-coating system would tend to increase application costs.

The slopes and intercepts of these figures are most revealing. The greater slopes of the case III curves over cases I and II point out the greater potential in drag reduction from the large areas in the inspar regions. Also, the low slopes of the case I curves indicate that, regardless of application costs, coating only the leading edges will not produce benefits. The intercepts of these curves are the cost differentials between coating and painting. They reveal the impact of the multiple recoating of the leading edges (for example, Astrocoat every 1745 hr as predicted by rain erosion tests) and the attendant large AOG losses.

Table 28. 45 000-hr Cycle Costs for Paint/Coating Applications

Applications	Paint application			Astrocoat application			CAAPCO application			Chemglaze application		
	Case I	Case II	Case III	Case I	Case II	Case III	Case I	Case II	Case III	Case I	Case II	Case III
Factory application												
Number of applications			1	1	1	1	1	1	1	1	1	1
Flow hours			63	106	106	106	84	84	84	74	74	74
Labor manhours			56	59	80	192	55	74	174	39	48	96
AOG dollar/application												
Labor dollar/application			1764	1859	2520	6048	1733	2331	5481	1229	1512	3024
Material dollar/application			1558	1045	1884	6914	928	1673	6140	297	536	1966
Total dollar/cycle	0	0	3322	2904	4404	12 962	2661	4004	11 621	1526	2048	4990
Field leading edge recoat												
Number of applications	17	17	17	23	23	23	5	5	5	14	14	14
Flow hours				106	106	106	84	84	84	74	74	74
Labor manhours	4	4	4	68	68	68	64	64	64	48	48	48
AOG dollar/application				11978	11978	11978	9492	9492	9492	8362	8362	8362
Labor dollar/application	126	126	126	2142	2142	2142	2016	2016	2016	1512	1512	1512
Material dollar/application				1045	1045	1045	928	928	928	297	297	297
Total dollar/cycle	2142	2142	2142	348 795	348 795	348 795	62 180	62 180	62 180	142 394	142 394	142 394
Field total recoat												
Number of applications			2	2	2	2	2	2	2	2	2	2
Flow hours			63	106	106	106	84	84	84	74	74	74
Labor manhours			98	68	96	249	64	90	231	48	64	153
AOG dollar/application			7119	11978	11978	11978	2016	2835	9492	1512	2016	8362
Labor dollar/application			3087	2142	3024	7844	928	1673	7277	297	536	4820
Material dollar/application			1558	1045	1884	6914	928	1673	6140	297	536	1966
Total dollar/cycle	0	0	23 528	6374	9816	53 472	5888	9016	45 818	3618	5104	30 296
Total cycle cost	2142	2142	28 992	358 073	363 015	415 229	70 729	75 200	119 619	147 538	149 546	177 680

* Field leading edge buffing

** Field Total repaint

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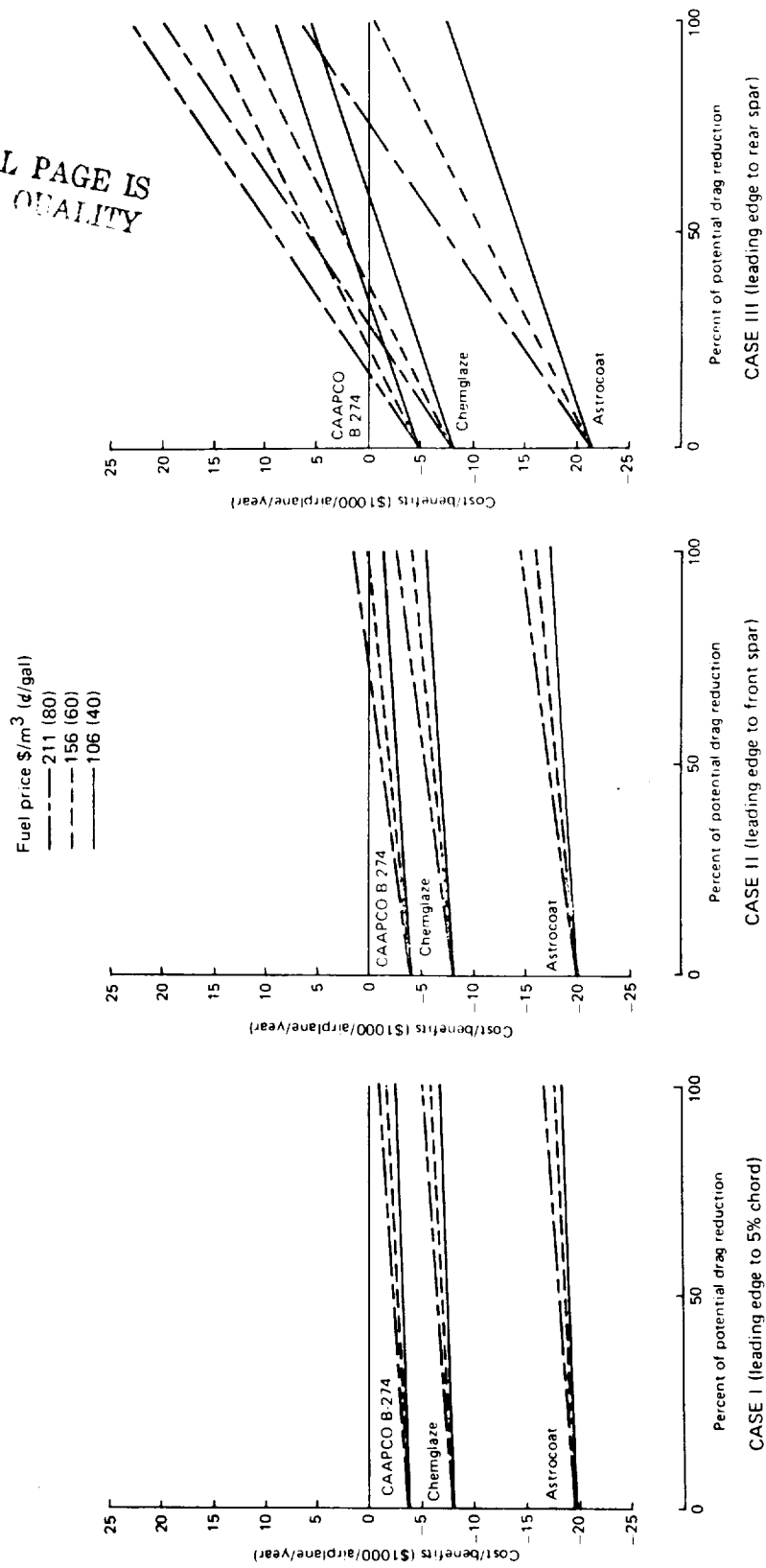


Figure 12. Cost/Benefits of Coatings

The study assumption that all airplanes in the fleet encounter rain on every third flight is considered an extreme environment. A 1975 Boeing survey revealed that only 11% of 975 727-200s surveyed experienced "severe" erosion problems. The term "severe" is subjective, since no quantitative values were applied to it. In this regard, a more quantitative survey of today's fleet is required to provide the proper distribution of airplanes encountering various degrees of erosion-producing environments. This distribution could then be used to reassess average fleet recoating times for each coating.

In terms of annual fuel savings for a 2000-airplane fleet of 727-type aircraft, the case III benefit could be as high as 261 000 m³ (69 million gal) per year, if the maximum potential drag reduction were realized. Likewise, the annual fleet cost benefits would be in the order of \$17 million at today's fuel prices.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on analysis of study results, supplemented with Contractor experience gained outside the study from the application of a wide variety of films and coatings to Contractor products.

5.1 CONCLUSIONS

- Spray-on coatings are superior to adhesively bonded films for erosion protection in areas exposed to high-velocity rain and particle impact. Rain erosion testing at 224 m/s (500 mi/hr) showed the coating life to be an order of magnitude greater than the erosion life of film/adhesive systems of comparable thickness
- Spray-on elastomeric polyurethane coatings exhibited the greatest durability in the rain erosion test environment. Test conditions were:

Drop size	0.7 mm
Rate	2.54 cm/hr (1 in/hr)
Velocity	224 m/s (500 mi/hr)

- Polyurethane coatings are susceptible to deterioration from prolonged exposure to hydraulic fluid of the type used in commercial transports
- Film applications over large areas do not appear to be feasible with currently available materials and/or application technology. Although films have been successfully applied to large areas in laboratory environments, the prohibitive costs associated with production line or field applications would make this process commercially unattractive. A strong, durable bond in areas of compound curvature requires a cast film (currently unavailable in large sheets) preformed to contour. Excrescences must be eliminated prior to applying the adhesive, rather than relying on the film and a variable-thickness of adhesive to mask the excrescence
- The estimated drag reduction on a 727 transport, from smooth (2-mil roughness) liquid coatings applied from the leading edges to the rear spars of wing and empennage surfaces, could be as much as 1.6%. Based on a utilization of 7.06 hours/day (fleet average), the annual fuel saving per airplane would be about 128.7 m³ (34 000 gal)
- It is estimated that if only 35% of the potential drag reduction were realized from the coating application noted above, the costs of application and maintenance would be offset by the reduction in fuel costs (fuel at \$106/m³ (40¢/gal))

5.2 RECOMMENDATIONS

- Flight/wind tunnel tests are necessary to measure the drag reduction from surface coatings applied to various areas of transport-type aircraft. The drag benefits should be measured against various baseline surface conditions

- Unless a distinct advantage can be shown for slick films over smooth coatings for drag reduction, the development of coating technology should be pursued with a higher priority than that for films. It is not clear, at this time, that films offer an advantage over smooth coatings even on surfaces designed for laminar flow
- Experience in the large-scale application of coating (and especially film) materials is needed to develop procedures for surface preparation, materials application, and repair and maintenance
- Service evaluations should be conducted in an airline operating environment to assess the durability of coatings when exposed to all typical air and ground environmental factors. It would be desirable to conduct the evaluations over an extended period of time, to include evaluations of maintenance and repair procedures.
- The preliminary cost/benefits analysis performed at the conclusion of this study should be reviewed and updated to reflect the results of the above-recommended actions.

6.0 REFERENCES

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2. Boeing Airliner Magazine, January 1974
3. Beasley, William D. and McGhee, Robert J., "An Exploratory Investigation of the Effects of a Thin Plastic Film Cover on the Profile Drag of an Aircraft Wing Panel," NASA Technical Memorandum 74073, October 1977
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APPENDIX A

ABSTRACTS OF PREVIOUS WORK

1. Air Micronesia Service Test, The Boeing Company, October 1977, unpublished.

Objective

Service test of materials to prevent erosion of aluminum leading edges.

Description

The following materials were applied in the Boeing Materials Laboratory to a 727 leading-edge slat and a 727 horizontal stabilizer leading edge:

- a. 0.012 polyurethane tape, 3 M Company
- b. 0.012 MIL-C-83231, Astrocoat, Olin Corp.
- c. 0.010 Kynar 500, Pennwalt Corp.
- d. 0.005 CRES, bonded
- e. 0.010 CRES, bonded

A 727 leading-edge slat was returned for evaluation from Air Micronesia after 2400 flight hours (about 3000 landing cycles over 10 mo). Air Micronesia operates in some of the world's worst rain erosion conditions.

Results

The CRES test areas showed no erosion but the CRES caused severe corrosion of the aluminum beneath. The polyurethane tape and the Kynar 500 film had peeled off by 581 flight hours. The Astrocoat was intact with the exception of minor chipping on the inboard edge and one small area on the leading edge.

2. Ansett ANA Service Test, The Boeing Company, September 1977, unpublished.

Objective

Protect engine nose cowl from erosion.

Description

Ansett applied a silicone coating to one 727 nose cowling. Exact film thickness is not known, but Boeing recommended 0.13 to 0.25 mm (5 to 10 mil) dry film thickness.

Results

After 2500 flight hours, the coating was in excellent condition.

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3. Howard, W.M., "Wind Tunnel Tests of Kynar (PVF 2) Film Coating," The Boeing Company, January 1976, unpublished.

Objective

Test a Kynar-coated wing section to determine its resistance to dirt and oil buildup and to abrasion.

Results

Kynar showed no improvement to dirt and oil buildup, but did show abrasion resistance superior to aluminum during the 1-mo test period.

4. Brooks, G.W., "Icing Tunnel Tests," The Boeing Company, June 1976, unpublished.

Objective

Test plastic materials to determine their ice-shedding characteristics.

Description

The following plastic materials were applied to wind tunnel test models and evaluated for their ice-shedding characteristics:

- a. Kynar (polyvinylidene fluoride)
- b. Teflon (FEP and TFE)
- c. Polyvinyl chloride
- d. Polycarbonate
- e. Nylon
- f. Chlorotrifluoroethylene
- g. Phenolic
- h. Polyethylene
- i. Acrylic (polymethyl methacrylate)
- j. Synthetic rubber (Seilon)
- k. Alkyds
- l. Epoxies
- m. Cellulose acetate
- n. Silicones

Results

None of the materials tested has suitable ice-shedding characteristics for auto-release of ice.

5. Beasley, William D.; and Robert J. McGhee, "An Exploratory Investigation of the Effects of a Thin Plastic Film Cover on the Profile Drag of an Aircraft Wing Panel," NASA Technical Memorandum 74073, October 1977.

Objective

Measure the reduction in profile drag from a smooth film applied to an NACA 65-213 airfoil section.

Summary

A 0.84m (33-in) span section of a T-33 wing was tested at a Mach number of 0.15 in the Langley Research Center low-turbulence tunnel. Test Reynolds numbers ranged from 7×10^6 to 63×10^6 . At low R_n , with a thin Kapton film covering the surface, the drag decreased to values approximating those for an aerodynamically smooth NACA 6-series laminar flow airfoil. At high R_n , with essentially full-chord turbulent boundary layer, a drag reduction of about 12% was measured.

6. Alexander, J. G., "Conductive Coatings for Composite Aircraft Surfaces," AFML-TR-77- (to be released), September 1977.

Objective

Develop conductive antistatic coatings for nonmetallic aircraft skins.

Results

Standard polyurethane coating systems were modified by incorporating metallic pigments to achieve desired antistatic characteristics.

Conclusions

Films for smooth wing application may cause requirement for antistatic coating.

7. "Electrodeposited Nickel Coatings for Erosion Protection," AFML-TR-70-111, July 1970.

Objective

Develop improved techniques for the electrodeposition of nickel, a superior coating for erosion resistance, onto fiber-reinforced-epoxy composite and aluminum substrates.

Results

The program results are discussed under five major headings: Adhesion, Nickel Deposits, Electroforming, Rain Erosion Protection, and Sand Erosion Protection.

Adhesion. Surface conditioning techniques are described for glass-epoxy, graphite-epoxy, boron-epoxy, and aluminum. In each case, satisfactory adhesion was achieved for the rain erosion tests, but sand erosion tests indicate that adhesion may be a problem. A combination of sand blasting and chemical treating is necessary for satisfactory adhesion to the composites. Heat treatment of the aluminum is recommended for improving adhesion of soft nickel, but it is cautioned that heat treatment of hard nickel depositions may induce brittleness.

Nickel deposits. Several different nickel compositions were evaluated. Tables of mechanical properties of both hard and soft nickel are presented.

Electroforming. Electroforming of the nickel followed by secondary adhesive bonding of the coating to the various substrates was studied as a means of improving coating adhesion. Adhesives and curing cycles are presented. The results were not conclusive enough to establish the superiority of either the electroplating or electroforming technique.

Rain erosion protection. Samples of materials were tested on the AFML/Olin test rig at 805 km/hr (500 mi/hr) in 2.45 cm (1 in) of simulated rainfall. The aluminum samples were electroplated to 0.15, 0.23, and 0.30 mm (6, 9, and 12 mils) of hard nickel. The glass epoxy materials were electroplated to the same thicknesses of soft nickel. All thicknesses of nickel passed a 120-min exposure test on aluminum. Only the 0.30 mm (12-mil) nickel on glass-epoxy passed the same test.

Sand erosion protection. The same samples that survived 120 min in rain were subjected to sand impact of 853 km/hr (530 mi/hr), 340 g/min on the same test rig. Data are charted and discussed. The nickel coatings showed a marked improvement over other coating materials previously evaluated. There was some indication that hard nickel was superior to soft nickel in this environment.

Conclusions

- a. The minimum nickel coating thickness required to protect the substrate was 0.23 mm (9 mils) for the composites and 0.08 mm (3 mils) for the aluminum.
- b. Adhesion was not a problem in the rain environment. Adhesion was a distinct problem for all substrates during the more severe sand testing.
- c. Electroforming and secondary bonding may offer advantages over electrocoating; however, proper surface preparation and void-free bonding must be attained or erosion rate will increase.

8. Air Force Materials Laboratory Sponsored Coating Development Programs.

Objective

Develop improved rain-erosion-resistant coatings for advanced design aircraft radomes. In some instances, high thermal-flash resistance is an added objective.

Results

Polyurethane coating materials have been developed that represent the current state-of-the-art for rain-erosion-resistant coatings (refs. 1 and 2). Room-temperature-curing fluoroelastomer compositions initially developed at the Air Force Materials Laboratory (ref. 4) were further developed into usable, thermally stable rain-erosion-resistant coatings (refs. 3, 5, and 6). These coatings are elastomeric in nature and possess excellent stability under long-term exposure at 260°C (500°F), and good rain-erosion resistance as measured on a rotating-arm apparatus. Attempts have been made to develop antistatic rain-erosion coatings for radomes (ref. 7). This effort met with limited success in achieving the conductivity and sacrificed rain-erosion performance because of high pigment volume concentrations.

The most recent work in this area (ref. 8) was an AFML-sponsored Avco program to develop erosion-resistant, antistatic thermal flash resistant coatings. A white fluoroelastomer coating overcoated with a black antistatic fluoroelastomer coating was recommended for radome applications.

Conclusions

- a. Polyurethane coatings are considered the state-of-the-art materials for airplane rain-erosion protection (refs. 1 and 2).
- b. Fluoroelastomer coatings have been developed with good rain-erosion resistance, thermal-flash resistance, and antistatic properties (refs. 3, 5, and 8).
- c. A black antistatic fluoroelastomer over a white fluoroelastomer coating is recommended as the most suitable erosion-resistant, antistatic, thermal-flash-resistant aircraft coating system (ref. 8).
- d. Polyurethane coatings based on cycloaliphatic isocyanates and polyester polyols have exhibited promise as protective coatings for metal aircraft leading edges (ref. 8).

References

1. Moraveck, J., and G. H. Clarke, "Rain and Sand Erosion Resistant Polyurethane Protective Coatings," AFML-TR-67-227, part II, Olin Corp., New Haven, Conn., July 1969.
2. Schmitt, G. F., Jr., "Fluoroelastomer Coatings Resistant to Thermal Flash, High Temperature, and Subsonic Rain Erosion," AFML-TR-74-25, April 1974.
3. Moraveck, J. F.; and H. G. Barnowski, "High Temperature Stable Subsonic Rain Erosion Resistant Fluoroelastomer Coatings Development," AFML-TR-75-59, Olin Corp., New Haven, Conn., May 1975.
4. Griffin, W. E., "Room Temperature Vulcanization of Fluorinated Hydrocarbon Elastomers," U.S. Patent 3,041,316, June 26, 1962.
5. Schmitt, G. F., Jr.; L. M. Peterson, and W. R. Griffin, "High Temperature Rain Erosion Resistant Fluoroelastomer Coating," AFML-TR-71-196.
6. Viager, R. L., "High Temperature Subsonic Rain Erosion Resistant Fluoroelastomer Coatings," AFML-TR-73-237, Olin Corp., New Haven, Conn., November 1973.
7. Griffin, R. H.; et al., "Electrically Conductive Coating Materials," General Electric Company, AFML-TR-207, part I, August 1973, part II, October 1974.
8. Moraveck, J. F., "Erosion Resistant, Antistatic Thermal Flash Resistant Polymeric Coatings," AFML-TR-76-186, Avco Systems Division, November 1976.

9. Dryden Flight Research Center, Edwards AFB, California, "Laminar Flow Tests to Eliminate Insect Adhesion on Aircraft Wings," NASA Brief No. 76-190, December 1976.

Objective

The objective of this program was to study techniques and materials to prevent insects from adhering to aircraft wings. Teflon-coated panels, panels coated with a material similar to that on aircraft windshields, and bare aluminum panels, all approximately 45.7 cm (18 in) wide, were installed on the leading edge of a Jet Star test aircraft. Instrumentation probes, installed above the panels, were used to determine changes in airflow characteristics. The test aircraft generally (1) flew at a low altitude, impacting a large number of insects, (2) landed for measurement of wing condition, and (3) climbed to a high altitude to measure the effects on airflow.

Results

Preliminary results indicated that a combination of material treatment and a washer system could be effective in preventing insects from adhering to the leading edge.

10. Alexander, J. G.; K. M. Jacobs, and G. W. Christiansen, "Smooth Wing Preproposal Effort," Avco System Division, 1976 (report not formalized).

Objective

Define material candidates for smooth wing applications.

Results

Numerous vendor contacts were made and samples of material candidates procured. Material recommendations were made based on review of available property data and cost considerations.

11. Brandel, W. W., "Reduction of Drag Over Airfoil Wing Surfaces of Aircraft," Avco correspondence.

Objective

Determine preliminary cost and procedure for application of plastic films to wing surfaces.

Results

A description of four potential methods for smoothing wing surfaces were presented with a labor and materials cost breakdown for each. The methods compared were:

- a. Adhesive-bonded solid film system
- b. Fill-and-paint system
- c. Adhesive-backed tape system
- d. Adhesive filler and release film system

Conclusions

All four systems appear cost competitive depending largely on cost of materials selected.

12. Springer, G. S., "Erosion by Liquid Impact," John Wiley & Sone, 1976.

Description

This book presents a compilation of existing knowledge on multiple-impact rain-erosion effects. It includes a comprehensive bibliography covering rain-erosion test data through 1974.

Results

The author presents analytical models that permit prediction of the onset of erosion damage and the erosion rates for both monolithic and coated surfaces. Properties of a number of materials are compiled for use in the prediction models. Data correlations are presented to substantiate the model.

Conclusions

This book is a useful source for entering the literature. The analytical techniques should be applicable for evaluating coating concepts and for defining optimum coating properties.

13. Yeager, R. E., "Hydraulic Tearing of Paint by Rain," E-Systems, Inc., December 1976.

Objective

The objective of this study was to investigate the tearing and lifting of forward edge aircraft paint when flying through rain and to establish prevention techniques.

Description

A test program was undertaken to investigate factors that could minimize the effects of rain without requiring a basic change in the paint system. Tests were conducted at the Air Force Materials Laboratory using their rotating arm rig. Materials investigated consisted of the following combinations coated onto 2024-T4 aluminum:

- a. BMS 10-70 primer and MIL-C-83286 topcoat
- b. BMS 10-79 primer and BMS 10-60 topcoat
- c. MIL-P-2337 primer and MIL-C-83286 topcoat

Results

- a. Paint damage did not occur when paint edges were located at, and aft of, the 25% chord line.
- b. Paint damage did not occur when paint edges were located at, and aft of, the 20% chord line and the paint edges were less than 0.05 mm (2.0 mils) thick.

- c. Paint damage did not occur when an erosion-resistant clear tape (3M SJ-8561) was applied over the entire leading-edge surface.

Conclusions

- a. Modify paint requirements and application procedures to limit total paint thickness on the upper surface of leading edge parts to 0.05 mm (2.0 mils) maximum. Fair forward paint edges as required to eliminate abrupt steps.
- b. Modify paint configurations so that the forward paint edges on leading edge parts are located aft of the erosion zone.
- c. There appeared to be no great difference in the erosion or peel resistance of the three paint systems evaluated.

14. Head, R. E., "Erosion Protection for the AH-1G Low Radar Cross Section Main Rotor Blade, Volume 1--Sand and Rain Erosion Evaluation," USAAMRDL-TR-76-40A, January 1977.

Objective

The objective of this program was to evaluate and select materials for protection of the AH-1G helicopter blades from rainy and sandy environments.

Results

A number of candidate coating materials were screened for suitability in a rotating-arm rain-erosion rig. Two materials, an ultrahigh molecular weight polyethylene and an adhesive backed polyurethane sheet supplied by Dunlop's rubber division, were selected for advanced rain and sand erosion testing. These two materials behaved differently during the advanced evaluation. The polyurethane eroded gradually; the UHMWPE took on a peened wavelet appearance in the sand exposure and eventually wore through. The Dunlop polyurethane was superior in all respects, including rain-erosion life, sand-erosion life, wear patterns, and ease of installation and removal.

Conclusions

The Dunlop polyurethane was selected to protect the main rotor blade.

15. Schmitt, G. F., Jr., "In-Service Performance of Polyurethane and Fluorocarbon Rain Erosion Resistant Radome Coatings," Ninth National SAMPE Technical Conference, October 1977.

Objective

The objective of this paper was to review the development and application of state-of-the-art polyurethane rain-erosion resistant coatings to airplane leading-edge surfaces. Fluorocarbon elastomeric coatings were also to be discussed as the next generation of radome protective coatings.

Results

The Air Force used MIL-C-7439B (black) and MIL-C-27315 (white) neoprene coating for protection of aircraft radomes until about 1969. Research initiated at the Air Force Materials Laboratory in 1965 resulted in improved radome protection materials currently used by the Air Force: MIL-C-83231 (black) and MIL-C-83445 (white), both of which are polyurethanes. The polyurethanes have eliminated erosion problems on many aircraft; however, they are limited in service temperatures to 150°C (302°F). At temperatures above 299°C (392°F), the polyurethanes lose their elastomeric character and erode rapidly.

Recent development work has resulted in fluorocarbon coatings with long-term stability up to 260°C (432°F) and substantial subsonic rain-erosion resistance. This coating withstands rain conditions of 25 mm/h (1 inch/hr) at 223 m/s (732 ft/s) for an average of 100 min.

Conclusions

Two coating systems are available that offer significant capability for aircraft radome subsonic rain-erosion resistance. MIL-C-83231 and -83445 polyurethanes provide rain protection where the temperature does not exceed 150°C (302°F). A new fluoroelastomer coating is available for higher temperature radome applications.

16. Fyall, A. A.; and R. B. King, "Guide to Rain Erosion," Royal Aircraft Establishment, January 1977.

Objective

The objective of this paper was to furnish a history of rain erosion, to outline problem areas and typical examples of component failures, and to present examples of rain-erosion performance of various materials.

Results

This paper presents the rain-erosion performance of a wide range of aerospace materials, including reinforced plastics, inorganic nonmetallics, and metals. Different experimental techniques are discussed and analytical techniques provided to predict the rain-erosion behavior of many different materials.

A short section, "Maintenance and Repair of Protective Coatings," describes practical considerations involving aircraft after flight at high speed.

17. Engle, O. G.; and A. J. Piekutowski, "Investigation of Composite Coating Systems for Rain Erosion Protection," UDRI-TR-71-47, University of Dayton, November 1971.

Objective

The objective of this program was to investigate composite coatings consisting of a soft polyurethane overcoated with a hard polyurethane for resistance to high-speed water drop impingement.

Results

Eight polyurethane composite coating systems having topcoats of relative hardness and undercoats of relative softness were tested for rain-erosion resistance. It was determined that, for 52 specimens tested, the composite coatings outperformed single layer coatings of the same materials. A change in erosion resistance could be detected only when the hardness difference between the top and bottom coats was 35 to 40 Shore A units.

It appeared that slow moisture cured polyurethanes produced better rain-erosion resistance than those cured by adding an additional component.

Conclusions

- a. A composite coating provides a greater reduction in the rate of loading of the substrate than a single layer coating.
 - b. The stress levels and the rate of loading at the substrate are higher when the softer coating overcoats the harder coating than when the harder coating overcoats the softer coating.
18. Knight, W. E., "AMLGUARD, A Corrosion Prevention Compound for Military Application," Naval Air Development Center, October 1977.

Objective

The objective of this work was to develop a corrosion-preventive paint compound for use on carrier-based naval aircraft.

Results

An extensive development program was conducted during which many materials were screened. Several different methods were used to evaluate corrosion protection, including:

- a. Outdoor exposure tests
- b. High-humidity cabinet tests
- c. Exposure in standard 5% salt fog cabinet
- d. Exposure in special salt fog cabinet to which SO_2 is periodically added
- e. A specially designed synthetic seawater sulfurous acid spray chamber

The most suitable formulation of those evaluated contained a silicone alkyd resin, two silicone resins, two corrosion inhibitors, a thickening agent, a coupling agent, and solvents. This formulation is referred to as AMLGUARD and is covered by MIL-C-85054 (AS).

Conclusions

AMLGUARD is a recommended inservice treatment for use on any bare metal or on painted metal where the paint coating has been damaged. Preliminary reports from service testing show that AMLGUARD works well as protection of the leading edges of the wings and tail of F-14 airplanes. No service exposure conditions were reported.

19. Behmke, D. L., "Evaluation of Protective Coatings Applied Under Adverse Conditions," Ninth National SAMPE Technical Conference, October 1977.

Objective

The objective of this investigation was to evaluate the corrosion-preventive characteristics of coating systems applied under adverse surface preparation and pretreatment primer conditions.

Results

Extensive testing was performed on twenty coating materials under widely varying surface preparation and application conditions. Screening tests consisted of 4 mo exposure to a 24-hr cycle simulating a marine environment. The ten best materials were then subjected to a one-year cycle in a specially designed test rig, again to simulate a marine environment. After one year all test planes exposed to marine atmosphere/seawater spray were rated good to excellent, with six of the ten exhibiting excellent performance even after application over rusty surfaces.

Conclusion

MIL-P-24441 polyimide epoxy was the best coating system evaluated. It tolerated adverse application conditions extremely well and, at a thickness of 0.20 mm (8 mils), protected structural steel exposed to flight deck launch area environments.

20. Moraveck, J. F., "Flight Tests of Erosion Resistant, Antistatic Thermal Flash Coatings," September 1977.

Objective

The objective of this program was to evaluate the inservice performance of a white polyurethane leading-edge coating. The coating was applied to four T-38 airplanes. The wing leading edges, horizontal and vertical stabilizers, and engine intake lips were coated with approximately 0.20 mm (8 mils) of materials. The coating was performed in September 1977 and the aircraft was to be periodically monitored.

21. Moraveck, J. F., "Erosion Resistant, Antistatic, Thermal Flash Resistant, Polymeric Coatings," Summary Report (to be released).

Objective

The objective of this program is to continue the development of advanced elastomeric polyurethane and fluoroelastomeric coatings to meet future aircraft radome needs.

Results

White thermal-flash-resistant and rain-erosion-resistant polyurethane coatings for metal leading edges were developed. These coatings are easy to apply under uncontrolled conditions and resist erosion up to 120 min on the AFML rotating arm apparatus. This work also includes the establishment of an AFML rotating arm apparatus at Avco, Wilmington, Mass.

Conclusions

Rain erosion testing was performed on identical materials in two rotating-arm test rigs, one located at AFML in Dayton, Ohio and one located at Avco in Wilmington, Mass. The average time to failure on the Avco rig is about 50% less than the time to failure on the AFML rig; however, the relative performance of the several materials tested was the same in both test facilities.

22. Schmitt, G. F., Jr., "Rain Erosion Behavior of Graphite and Boron Fiber Reinforced Epoxy Composite Materials," AFML-TR-70-316, March 1971.

Objective

The objective of this study was to determine the rain-erosion behavior of graphite-epoxy and boron-epoxy composites, materials which are representative of advanced structural components for airplanes.

Results and Conclusions

The substrates were investigated uncoated, coated with polyurethane and coated with electroplated nickel. It was concluded that boron- and graphite-epoxy composites must be protected from rain erosion, even at subsonic velocities, as is also the case for glass reinforced materials. Polyurethane coatings offered limited protection in a subsonic rain environment but did not give sufficient resistance for long-term exposure conditions. The use of electroplated nickel was required to obtain substantial subsonic protection of these materials.

23. Fyall, A. A.; and R. B. King, "Rain Erosion Characteristics of Concorde," Royal Aircraft Establishment.

Objectives

This paper describes the British Civil Aviation Authority rain requirements developed for the Concorde and summarizes flight profile analyses and experimental data from tests with: a) a whirling arm, b) a rocket sled, and c) flights through rain by a Phantom aircraft.

Results

Tests and analyses resulted in a discussion of a model hydrometer atmosphere which indicates the horizontal and vertical extents and intensities of cloud droplets, rain, hail, and ice crystals. Details were published in document form as "A Proposed Model Hydrometer Atmosphere for Aircraft Design Purposes," RAE Technical Memorandum ME 270.

An assessment of rain erosion hazards established test conditions for simulated Concorde flight by a Phantom aircraft. The test conditions were velocities ranging between 257 to 412 m/s (500 to 800 ktas) for normal ascent and descent to the from 12 200m (40,000 ft) under the following rain conditions:

- a. 927m (0.5 nmi) in a rain density of 20 g/m^2
- b. 5559m (3.0 nmi) in a rain density of 8 g/m^3
- c. 92 650m (50 nmi) in a rain density of 2 g/m^3
1 g/m^3 rain density for the remainder of the flight profile

Test results using three test techniques the whirling arm, rocket sled, and actual flight tests—are presented. In addition to the evidence from the specimen carried on the flight aircraft, the aircraft itself incurred damage. The leading edges had been protected by polyurethane, which apparently survived well, but paint and fillers were damaged as were reinforced plastic antenna covers and other plastic hardware.

Conclusions

The Phantom flight tests indicated that rain erosion inspection must be a part of each interservice overhaul. The flight tests established a high degree of confidence in materials and design, and reinforced the evidence from whirling-arm and sled tests that the Concorde would survive the required flight conditions.

Design criteria were established for minimization of damage, and included details of joints and elimination of all forward-facing lap joints.

24. Gregorek, G. M.; M. J. Hoffman, and G. S. Weislogel, Ohio State University and G. M. Vogel, Beech Aircraft Corporation, "In-Flight Measurements of the GA(W)-2 Aerodynamic Characteristics," 770461, Society of Automotive Engineers, March 29-April 1, 1977

Objective

Investigate the aerodynamic characteristics of a new low-speed airfoil (general aviation GA(W)-2) in flight.

Results

A Beech Sundowner was test flown with a full-span glove which produced a 13% GA(W)-2 airfoil. The tests included an evaluation of drag effects due to a 0.13-mm (5-mil) KAPTON film applied to both upper and lower surfaces.

Conclusions

Preliminary flight test results showed a possibility for surface coatings to reduce drag. Further study is warranted.

25. "Improved Erosion Resistant Polyurethane Coating for Aircraft Leading Edges." USAF Topical Report AFML 62101F/1L1R0074.

Objective

Flight test new chemically cured polyurethane elastomeric coating.

Summary

Repair of current moisture-cured polyurethane elastomer coatings (MIL-C-83231) and MIL-C-83445) is a significant cost on transport (C5, C141, C130, and KC135) and bomber (B-52) aircraft. Moisture-cured coatings require restrictive controls of temperature and humidity during application. Application of a new chemically cured polyurethane elastomer was evaluated in both dry and humid environments. No problems were encountered. The coating is being flight tested on leading edges of T-33 trainer aircraft. AFML estimated new coatings can save \$2 million per year if used on military aircraft.

26. "Smoothness of Corogard Coatings," The Boeing Company, unpublished.

Objective

Measure the roughness of Corogard and polyurethane coatings.

Summary

Wind tunnel testing of smooth flat plate samples of polyurethane and Corogard indicated polyurethane was "hydraulically smooth" whereas Corogard had a surface roughness equivalent to fine sandpaper. In terms of an equivalent sandgrain roughness height, k_s , Corogard had a roughness height of $k_s = 0.0015$ to 0.0030 . The variation of this value was due to the painting technique. For polyurethane the testing indicated $k_s = 0$. A satisfactory corrosion-resistant replacement for Corogard should improve fuel economy considerably.

APPENDIX B

SPECIAL TEST PROCEDURES

In the absence of standard test methods, Boeing procedures were followed to evaluate coating material hardness, reaction to cleaning and deicing solutions, erosion adhesion, and corrosion resistance. These test procedures are presented in this appendix.

Test	Boeing Procedure	Test Requirement Reference
Pencil Hardness	BMS 10-79, procedure 7.2.5	1.11, Table 6
Cleaning and Deicing Solutions	D6-17487, procedure 12.2 BAC 5744, paragraph 3a	2.2, Table 8
Erosion Adhesion	BMS 10-70, procedure &.2.14	2.5, Table 8
Corrosion (exfoliation)	Exfoliation corrosion test	2.7, Table 8

PENCIL HARDNESS—BMS 10-79, PROCEDURE 7.2.5

7.2.4 STORAGE STABILITY

Store previously unopened containers of primer base material, primer mixing solution and primer thinner (when required) at 65 to 100°F for 12 months. At the end of this period, test according to all requirements of Section 4.

7.2.5 POT LIFE

- Fill a pint (minimum) metal container with a tight fitting cover, to within approximately one-inch of the top with the mixed material originally prepared for spraying.
- Seal covered container aside undisturbed at 75 ± 5°F for 4 ± 0.5 hours.
- Conduct tests for items 9 and 11 of Table I.
- Spray apply the mixed material to test panels according to 7.1 and conduct all tests according to Table II.

7.2.6 DRY TIME

7.2.6.1 For Tape Marking

Prepare Alodine 1200 treated test panels according to Section 7.1 and allow primer on test panel to dry 2 hours. Press a strip of 3M Company Banner 330 tape down firmly to the primed surface. Allow to remain 16 to 24 hours. Remove tape and check for staining and marking.

7.2.6.2 For Compression

Allow primer on Alodine 1200 treated test panels to dry 2 hours. Spray apply a second coat of primer and allow to cure for 7 days. Conduct adhesion test according to Section 7.2.4.1.

7.2.5 PENCIL HARDNESS

a. Preparation of Pencils

Prepare a set of drawing pencils (KOH-I-NOOR 1500, Venus Drawing Pencils, A.W. Faber-Castell or Eagle Turquoise) ranging in hardness from 6B to 5H by stripping the wood away from the end approximately 3/8 inch without damaging the lead. Square the tip of the lead as shown in Figure 1, by holding the pencil in a vertical position and moving the lead back and forth over 400 grit or finer abrasive paper. Square the tip of the lead after each trial. Alternatively, drafting leads held in a clutch type holder such as Locktite 9400 may be used.

b. Prepare Alodine 1200 treated test panels according to Section 7.1 and cure for 7 days.

c. Procedure

Place the test panels in a horizontal position. Push pencils of increasing hardness across the coated surface of the panel at 45 degree angle (See Figure 1) until one is found which will cut through the coating. The number of this pencil shall be used to express the pencil hardness.

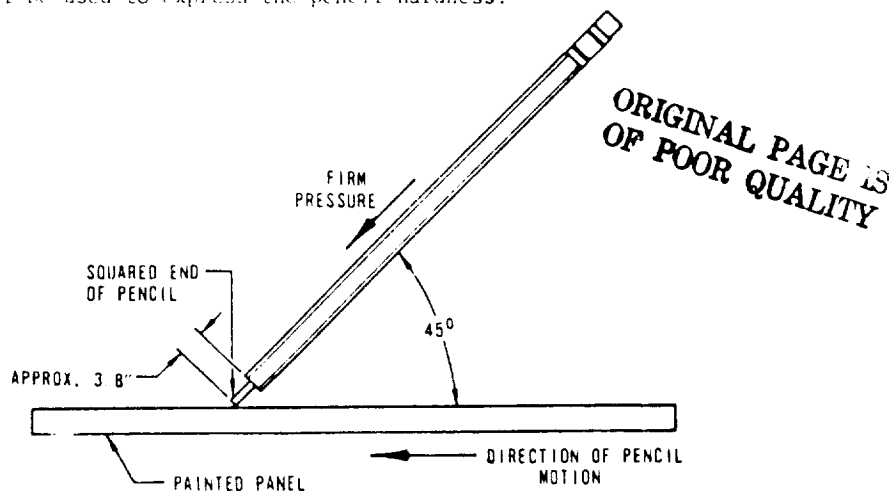


Figure B-1. Pencil Hardness Test
B-2

12.2 TEST PROCEDURE

- A set of Eagle Turquoise drawing pencils shall be used for this test. Each set will include one pencil each of the following lead hardnesses: 6H, 5H, 3H, 2H, H, F, HB, B, 2B, 3B, 4B, 5B, and 6B. The tip of the lead shall be squared by holding the pencil in a vertical position and moving the lead back and forth over 400-grit sandpaper. The tip of the lead shall be squared and cleaned with cheesecloth before each trial (see fig. B-2).
- Immerse one-half of each panel in a vertical position in the material being tested for 30 min at 38°C (100°F). The panels shall be rinsed with tap water and allowed to dry for 24 hr.
- Using pencils of increasing hardness and applying the pencils as shown in figure B-2, determine the number of the first pencil that will cut or scratch the film. This number indicates the pencil hardness. Apply the test first to the half of the panel which has not been subjected to the test material and then to the remaining half.
- The test material is rejected if the pencil hardness between both halves of each test panel varies by more than two pencils or if any discoloration is evident between the immersed and nonimmersed portions of each panel. Slight darkening of Corogard is acceptable.

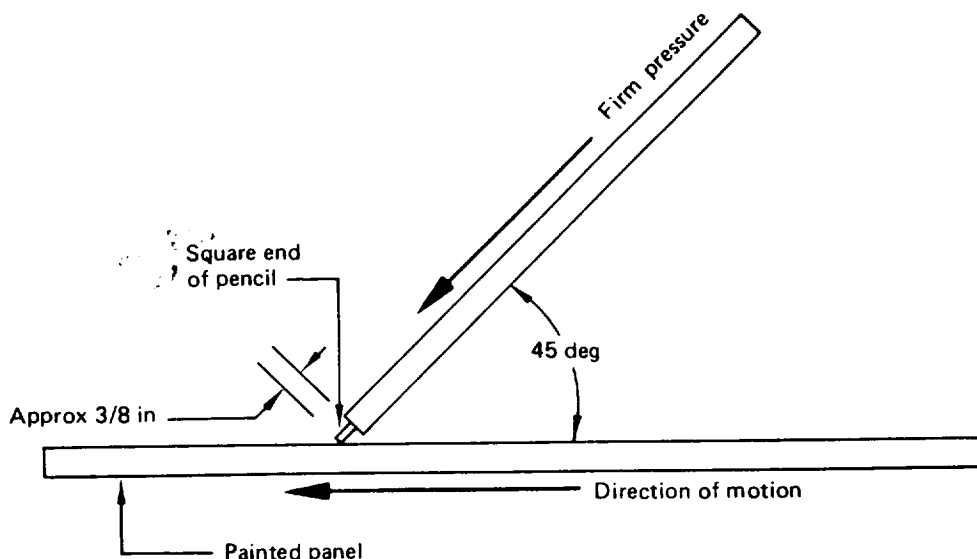


Figure B-2. Paint Softening Test



SCOPE

a. This specification describes manual cleaning by the following methods:

Method 1 General Cleaning

Method 2 Heavy Duty Cleaning

Method 3 Foam Cleaning

Method 4 Cleaning Interior Surfaces of Vessels and Tubes

b. Manual cleaning according to this specification is intended for cleaning of all metals, plastic and painted surfaces.

c. The emulsion cleaning per Method 2 of this specification meets the requirements of PP-C-490, Method IV when used for cleaning ferrous alloys.

d. Other processes meeting the requirements of PP-C-490 may be used by suppliers in lieu of this specification when emulsion cleaning ferrous alloys.

REFERENCES

None

MATERIALS CONTROL

a. Cleaners, Waterbase Alkaline, Liquid.

(1) GMC 528, Greater Mountain Chemical Company, Salt Lake City, Utah

(2) Kelite 28, Kelite Corporation, Los Angeles, California

(3) CeeBee 280, CeeBee Chemical Company, Downey, California

(4) Oakite 204, Oakite Products Company, New York, New York

(5) Pennsalt (Delchem) 2271R, Pennsalt Chemicals Corporation, Los Angeles, California

(6) Turco Jet Clean C, Turco Products Incorporated, Wilmington, California

(7) DuBois C-1102, The DuBois Company, Inc., Cincinnati, Ohio

(8) Calla 301, Midway Supply Company, Riverdale, California

(9) Tec Formula No. 1, Tec Chemical Company, Monterey Park, California

(10) Pacific Chemical B-82, Seattle, Washington

(11) Aerowash, Wyandotte Chemical Corporation, Wyandotte, Michigan

(12) Metaclean AC, Metasurf Corp., Detroit, Michigan

b. Solvent

Cleaning Solvent, General Purpose, EKS 3-2, Type 1, Flash Point 100F.

c. Cleaners for foam cleaning

Oakite 74-L. Oakite Products Company

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BY <u>W. W. Donahue</u>	W. W. Donahue MFG. <u>R. Jacobson</u>	MANUAL CLEANING (COLD ALKALINE, SOLVENT EMULSION AND FOAM CLEANERS)	BAC 5744 PAGE 1 OF 4
CK'D <u>P. B. Underhill</u>	QUAL <u>D. J. Lawrence</u>	BOEING PROCESS SPECIFICATION	
ENG <u>Joseph H. Rouse</u>	MAT'L <u>W. H. Rouse</u>		

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EROSION ADHESION-BMS 10-79, PROCEDURE 7.2.14

7.2.11 COMPATIBILITY WITH EPOXY PRIMERS

- a. Paint one set of Alodine 1200 treated test panels with BMS 10-11, Type I primer, according to BMS 10-11.
- b. Paint one set of Alodine 1200 treated test panels with BMS 10-10, Type II primer, according to BMS 10-10.
- c. Cure test panels for 30 days at $75 \pm 5^\circ$ or 24 hours at $125 \pm 10^\circ$.
- d. Hand sand primed surfaces with Scotchbrite pads, Type A, 36 Grits. Solvent clean panels with toluene.
- e. Apply primer according to Section 7.1 and cure 7 days.
- f. Conduct adhesion tests according to Section 7.2.8.

7.2.12 COMPATIBILITY WITH URTHANE ENAMELS

- a. Prepare separate sets of test panels with Alodine 1200 and Alodine 1200 cured according to Section 7.1 and allow primer to dry 2 hours.
- b. Apply BMS 10-60, Type II, white enamel according to BMS 10-60 and cure for 7 days.
 - (1) Type I - Final dry film thickness of enamel shall be 4.2 ± 0.2 mils.
 - (2) Type II - Final dry film thickness of enamel shall be 1.8 ± 0.2 mils.
- c. Conduct adhesion tests (Section 7.2.8) salt spray corrosion tests (Section 7.2.10) and hydraulic fluid resistance (Section 7.2.9).

7.2.13 LOW TEMPERATURE SHOCK

- a. Prepare Alodine 1200 treated test panels according to Section 7.1 and cure for 7 days.
- b. Subject test panels to 24 of the following cycles:
 - (1) 25 minutes at $160 \pm 5^\circ$ then within 5 seconds
 - (2) 5 minutes at $-25 \pm 5^\circ$
 On completion of the last cycle, place test panels in a cold box at $-25 \pm 10^\circ$.
- c. Expose test panels for 5 hours at $-25 \pm 5^\circ$.
- d. Bend test panels without removal from the cold box over a circular mandrel which has also been conditioned at $-25 \pm 5^\circ$.
- e. Evaluate condition of test panels. Conduct dry adhesion test (Section 7.2.8.1).

7.2.14 RAIN EROSION RESISTANCE *

- a. Prepare air foils to fit the Vertical Whirling Arm from clad 2024 aluminum (.063 inches thick) with Alodine 1200. Mask off the leading edge nose at $3 \pm 1/8$ inch from base of air foil on both sides. Apply Type II primer (freshly mixed) per Section 7.1. Allow primer to dry 2 hours.
- b. Apply BMS 10-60, Type II enamel per BMS 10-60, except dry film thickness shall be 4.0 ± 0.5 mils. Remove masking tape to expose paint edges within 8 - 24 hours after painting. Allow to cure 7 - 30 days.
- c. Immerse air foils in water at $75 \pm 5^\circ$ for 16 - 24 hours just prior to test. Start test within one hour after removal from water.
- d. Expose air foils to 390 miles per hour with 1 inch per hour water spray for 30 minutes.
- e. Check and measure erosion pitting from paint leading edges.

*NOTE: This procedure was modified to adapt to the characteristics of AFML rain erosion test rig used in the tests discussed in section 4.3.2.11.

CORROSION (EXFOLIATION)

Exfoliation Corrosion Test

1. Test Specimen Materials

- a. Top plate-7075-T6 bare aluminum, chromic acid anodized per MIL-A-8625 Type I prior to drilling and countersinking. Size: 15.24 x 7.62 x 0.64 cm (6 x 3 x 1/4 in).
- b. Center plate-2024-T3 bare aluminum, chromic acid anodized per MIL-A-8625 Type I prior to drilling. Size: 15.24 x 7.62 x 0.64 cm (6 x 3 x 1/4 in.) (Thickness may be increased to adapt to fastener length.)
- c. Baseplate-CRES 301, stainless steel passivated. Size: 25.4 x 12.7 x 0.32 ± 0.16 cm (10 x 5 x 1/8 ± 1/16 in.)
- d. Fasteners-phosphate fluoride-coated titanium, countersink head.
- e. Sealant-MIL-S-8802 polysulfide.

2. Specimen Assembly

- a. Drill holes, countersink, and assemble fasteners as shown in figure B-3. Hole size shall allow 0.025 to 0.127 mm (0.001 to 0.005 in) clearance fit. The fastener head shall be flush with the surface of the block within ± 0.254 mm (± 0.010 in) after installation.
- b. Clean and apply coating or film to countersink side of 7075-T6 aluminum top plate. Cure coating according to manufacturers or specification prior to test.
- c. Apply fillet seals to edges and fastener collars or nuts as shown in figure B-3.

3. Accelerated Exposure Procedure

The test specimen shall be exposed to the acetic acid spray test per ASTM B287 for 30 days.

4. Examination

After exposure, remove all fasteners in such a manner as to prevent deformation of the fasteners or the hole. Remove loose corrosion and salt deposits by lightly brushing in water and dry. Examine surfaces, countersink areas, and holes for exfoliation.

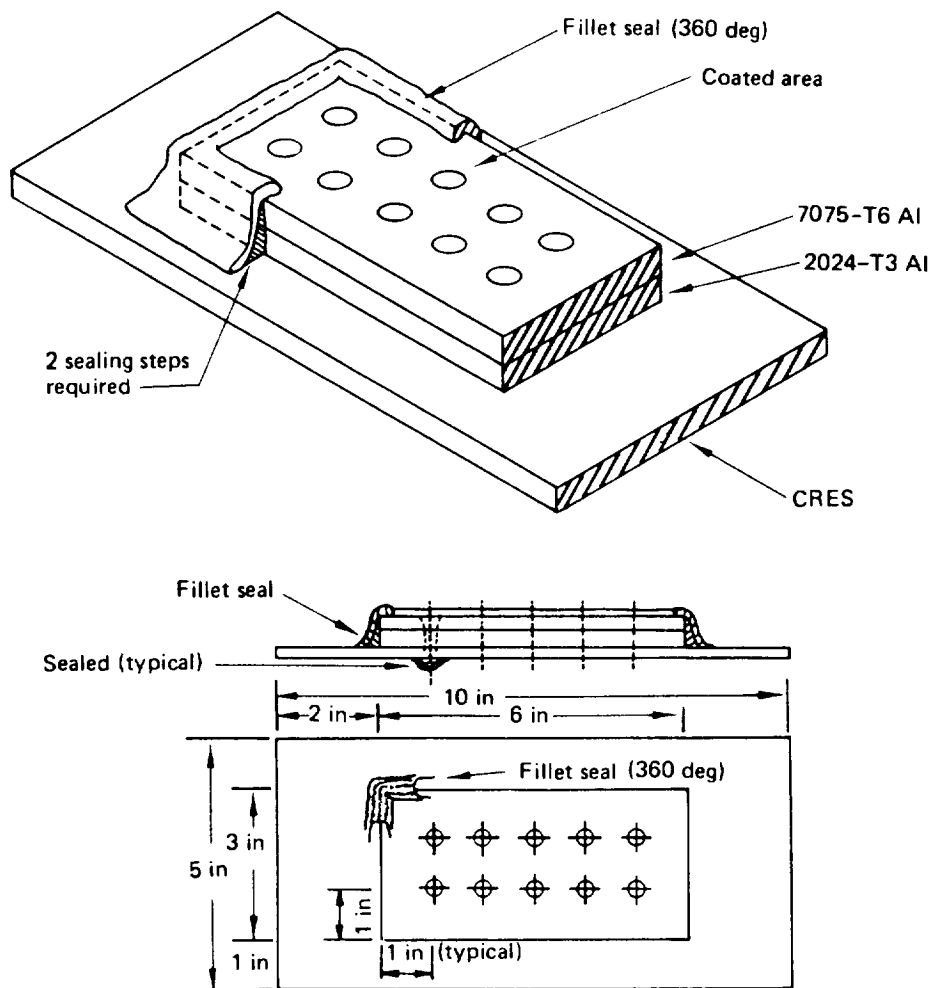


Figure B-3. Exfoliation Test Specimen (For Clarity, Coated Area Not Covered)

APPENDIX C

TEST RESULTS

NOTE: The results shown are averages for at least two specimens for all mechanical or physical property tests. Visual examination testing was generally based upon a single specimen exposed per the appropriate standard test requirements.

Table C-1. Peel Test Results (Screening Tests—Three Specimens of Each Film/Adhesive Combination)

Adhesive	Class	Film	Initial peel strength		Peel strength after fuel immersion	
			N/cm	(lb/in)	N/cm	(lb/in)
CONAP DP6298	Urethane	Tuftane	7.9	(4.5)	1.2	(0.7)
		Hituff	5.3	(3.0)	1.1	(0.6)
		Hituff	1.8	(1.0)	0.9	(0.5)
		Hituff	7.9	(4.5)	7.9	(4.5)
		Kapton	2.6	(1.5)	—	—
		Kapton	4.4	(2.5)	2.6	(1.5)
		Hytrel	10.2	(5.8)	—	—
		Hytrel	12.3	(7)	8.8	(5)
		Tradlon	<17.5	(<10)	3.5	(2)
		UHMWPE	2.8	(1.6)	0.4	(0.2)
		Hituff	8.8	(5)	3.2	(1.8)
		Hituff	4.4	(2.5)	4.4	(2.5)
Bostik 7124	Phenolic urethane	Hituff	7.0	(4)	—	—
		Hituff	8.8	(5)	—	—
		Kapton	4.4	(2.5)	—	—
		Kapton	7.0	(4)	7.0	(4)
		Hytrel	4.4	(2.5)	3.5	(2)
		Hytrel	0	(0)	—	—
		Tradlon	3.5	(2)	—	—
		Tradlon	0.5	(0.3)	—	—
Bostik 7064	Polyester	Hituff	5.3	(3)	3.5	(2)
		Hituff	8.8	(5)	—	—
		Hituff	7.0	(4)	5.1	(3.5)
		Kapton	4.4	(2.5)	—	—
		Kapton	21.9	(12.5)	—	—
		Kapton	7.0	(4)	High	(High)
Dupont 56065	Polyester	Hituff	0	(0)	—	—
		Kapton	5.3	(3)	7.0	(4)
		Kapton	15.8	(9)	12.3	(7)
		Kapton	4.4	(2.5)	—	—
		Mylar	4.4	(2.5)	High	(High)
		Hytrel	5.3	(3)	12.3	(7)
		Tradlon	0.9	(0.5)	—	—
		UHMWPE	4.4	(2.5)	—	—
Bostik 4045	Nitrile rubber	Hituff	1.8	(1)	—	—
		Kapton	0.9	(0.5)	—	—
		Kapton	3.5	(2)	7.0	(4)
		Mylar	3.5	(2)	12.3	(7)
		Mylar	0	(0)	—	—
		Tradlon	0.9	(0.5)	—	—

Table C-1. Peel Test Results-(Cont)

Adhesive	Class	Film	Initial peel strength		Peel strength after fuel immersion	
			N/cm	(lb/in)	N/cm	(lb/in)
Bostik 71328	Polyester	Kapton	0.9	(0.5)	—	—
		Hytrel	5.3	(3)	2.6	(1.5)
		Hytrel	0	(0)	—	—
Conastic 830	Acrylic	Hituff	0	(0)	—	—
		Kapton	0	(0)	—	—
		Hytrel	0	(0)	—	—
Adhesive 80	Fluoro	Kynar	8.8	(5)	2.6	(1.5)
		Tefzel	5.3	(3)	—	—
		UHMWPE	8.8	(5)	—	—
PR 1422A	Polysulfide	Hituff	0	(0)	—	—
		Kapton	15.8	(9)	15.8	(9)
		Hytrel	22.8	(13)	1.8	(1)
		Hytrel	21.0	(12)	—	—
		Mylar	3.5	(2)	—	—
		Kynar	0	(0)	—	—
		Tradlon	15.8	(9)	12.3	(7)
Densil 3078	Silicone	Hituff	8.8	(5)	—	—
		Kapton	7.9	(4.5)	—	—
		Kytrel	8.8	(5)	—	—
		Kynar	17.5	(10)	—	—
		Kynar	15.8	(9)	—	—
		UHMWPE	8.8	(5)	—	—
Commercial adhesive backed films		3M 8562	2.5	(1.4)	—	—
		Teflon-Joclin	1.8	(1.0)	—	—
		Teflon-CHR	5.8	(3.3)	—	—
		Polyolefin-TAC	15.1	(8.6)	—	—
		Polyolefin-TAC	11.9	(6.8)	—	—
		Polyolefin-TAC	12.3	(7.0)	—	—
		Kapton-TAC	3.5	(2.0)	—	—
REN RP 6401	Urethane	Hituff	<ul style="list-style-type: none"> • Specimen quality poor • Bad batch of adhesive • No tests 			
		Kapton				
		Mylar				
		Hytrel				
		Kynar				
		Tradlon				
REN DA-552-1	Urethane	Hituff	1.1	(0.6)	0.9	(0.5)
		Kapton	5.1	(2.9)	4.0	(2.3)
		Hytrel	4.0	(2.3)	2.5	(1.4)
		Kynar	9.8	(5.6)	12.4	(7.1)
		Tradlon	4.0	(2.3)	4.2	(2.4)

Table C-2. Liquid Coating Specifications

Concept Description	21, CAAPCO MIL-C-83231	22, Experimental CAAPCO	24, CAAPCO Type II fluoro- elastomer	25, DC3145	26, Sterling MIL-C-83231	27, BMS-10-60	28, M313 Chem- glaze	29, Dapcoat 3400CS
Shelf life (months)	12	No specifications established	12	Deleted	12	12	12	6
Condition in container*	Pass	—	Pass	—	Pass	Pass	Pass	Pass
Drying time (hours)	8	—	8	—	8	6	6	Overnight
Nonvolatile content (% weight)	40	—	12	—	55	52	65	60 + 5
Viscosity (centapoise), 25°C (77°F)	200-500	—	(30-50 sec) Zahn No. 2	—	200-500	(17 to 23 sec) Zahn No. 2	300-600	3000 ± 10 ³
Weight kg/l (lb/gal)	0.98 (8.2)	—	0.95 (7.9)	—	0.98 (8.2)	1.01 (8.4)	0.99 (8.3)	1.08 ± 0.06 (9.0 ± 0.5)
Spraying properties	Normal	—	Normal	—	Normal	Normal	Normal	Normal

* Free of lumps, skins, grit, and coarse particles

Table C-3. Free Films Test Results

Film	Test	1.16 Virgin		1.18 Heat age		1.19 Weatherometer		1.21 Jet fuel		1.21 Hydraulic fluid		
Kapton Hituff 3M8561 Hytrel 3M5690 Kynar Tradlon UHMW polyolefin	Tear Strength per ASTM D-624, Target = 333 N/cm (190 lb/in)											
		N/cm	(lb/in)	N/cm	(lb/in)	N/cm	(lb/in)	N/cm	(lb/in)	N/cm	(lb/in)	
	503	(287)	1138	(650)	683	(390)	2504	(1430)	1086	(620)		
	1086	(620)	968	(553)	876	(500)	823	(470)	Dissolved	—		
	—	—	—	—	—	—	—	—	—	—		
	1143	(653)	1051	(600)	Decomposed	—	—	828	(473)			
	—	—	—	—	—	—	—	—	—	—		
	1804	(1030)	1593	(910)	1663	(950)	1879	(1073)	1751	(1000)		
	350	(200)	1086	(620)	525	(300)	718	(410)	700	(400)		
	981	(560)	946	(540)	946	(540)	578	(330)	898	(513)		
Kapton Hituff 3M8561 Hytrel 3M5690 Kynar Tradlon UHMW polyolefin	Tensile Strength per ASTM 2370 (10 ⁻³)											
		N/cm ²	(lb/in ²)	N/cm ²	(lb/in ²)	N/cm ²	(lb/in ²)	N/cm ²	(lb/in ²)	N/cm ²	(lb/in ²)	
	21.0	(30.4)	17.8	(25.8)	15.1	(21.9)	3.6	(5.2)	20.8	(30.2)		
	5.7	(8.3)	4.3	(6.3)	3.6	(5.2)	5.8	(8.4)	Dissolved	—		
	—	—	—	—	—	—	—	—	—	—		
	5.8	(8.4)	3.6	(5.2)	Decomposed	—	—	3.2	(4.7)			
	—	—	—	—	—	—	—	—	—	—		
	5.2	(7.6)	5.0	(7.2)	5.2	(7.6)	5.1	(7.4)	5.2	(7.6)		
	12.6	(18.3)	12.8	(18.5)	9.4	(13.6)	2.3	(3.4)	12.2	(17.7)		
	2.7	(3.9)	2.6	(3.8)	6.9	(10.0)	5.1	(7.4)	2.6	(3.7)		
(Target) Kapton Hituff 3M8561 Hytrel 3M5690 Kynar Tradlon UHMW polyolefin	Shrinkage and Hardness											
	1.23 Shrinkage, %	1.24 Shore A hardness										
		Virgin					Heat aged					
	(Target)	(<5.0)	(60 \pm 5) *					(60 - 5 + 15) *				
	Kapton	0.2	93					93				
	Hituff	7.4	75					75				
	3M8561	0.7	76					76				
	Hytrel	0.4	90					90				
	3M5690	1.3	80					80				
	Kynar	0.9	80					80				
Tradlon	+0.5 (expansion)	94					94					
UHMW polyolefin	0.4	75					75					

* Erosion area films only

Table C-4. Flexibility and Abrasion Test Results

Test	1.10 Flexibility		2.10 Temperature/shock flexibility		2.13 Impact flexibility	2.14 Abrasion weight loss
Target	No cracking or loss of adhesion		No cracking or loss of adhesion		No cracking or loss of adhesion	0.035g/1000 rev
Concept	% elongation	Remarks	% elongation	Remarks	Remarks	
I	27.5	OK	27	OK	OK	0.007
II	33.5	OK	29	OK	OK	0.022
III	28.5	Fracture	29	Fracture	OK	0.002
IV	25.5	OK	26	OK	OK	0.005
V	29.5	Fracture	27	Fracture	OK	0
VI	27.5	OK	29	OK	OK	0
VII	27.5	OK	29	OK	OK	0
VIII	25.5	OK	26	OK	Debond	0
IX	25.5	OK	26	OK	OK	0.003
X	24.5	OK	25	OK	OK	0.002
XI	28.5	Debond	28	OK	Debond	0.007
XII	27.5	OK	26	OK	Debond	0.005
XIV	33	OK	32	OK	OK	0.003
XV	22	OK	23	OK	Cracked	0.011
XVI	28.5	OK	29	OK	OK	0.001
XVII	23.5	OK	25	OK	OK	0.001
21	32.5	OK	34	OK	OK	0.001
22	30.5	OK	31	OK	OK	0.004
24	31.5	OK	32	OK	OK	0.002
26	28.5	OK	30	OK	OK	0.007
27	33.5	Fracture	34	Fracture	Fracture	0.005
28	33.5	OK	35	OK	OK	0.001
29	33.5	OK	33	OK	OK	0.110

Table C-5. Peel Test Results -lb/in Width*

Concept	Film	Paragraph	1.13	1.8	Virgin screening	1.17	1.9	1.20	1.21	1.12	Jet fuel, 24 hr, room temp	Hydraulic 7 days, 490°C (1200°F)	Humidity, 30 days, 490°C (1200°F)	2.9	2.11	1.18	2.8
I	Kapton	PR1422	9.0	3.7/8.2 AA/CB		3.6 AP	2.0 AP	5.0 AP	9.0	7.5 CB	7.3 CB	4.0 AA	7.5 CB	9.5 CB	5.6 TF		
II	Hytrel	PR1422	13	6.6 CB			1.6 AA		10	6.0 CB	2.4 CB	8.4 CB	6.8 CB	6.3 CB	Decomposed		
III	Tradlon	PR1422	9.0	10.0 CB		5.0 AP	1.9 AA	10.0 CB	4 to 9.4	10.3 CB	8.5 CB	0.1 AF	0.6 AF	9.6 CB	8.0 CB		
IV	Hytrel	DPAD6298	7.0	4.7 AF			0.2 CB		5.0	Debond	Debond	7.0 CB	8.0 AF	9.3 TF	Decomposed		
V	Tradlon	DPAD6298	10	1.2 AF			0 AA		2.0	0.6 AF	1.0 AF	6.5 AF	6.8 AF	12.2 AF	20 TF		
VI	Hituff	DPAD6298	4.5	0.9 AF		1.8 AP	0.2 AF	0.4 AF	4.5	Failed	Dissolved	0.3 AF	0.7 AF	4.4 AF			
VII	Hituff	7064	4.0	7.0 CB		12.4 AP	0 AA	4.0 AP	3.5	8.0 AF	Dissolved	1.0 CB	7.1 AF	8.4 AF			
VIII	UHMW polyolefin	AB	7.0	6.8 CB		7.6 AP	9.4 CB	9.0 CB	6.1	0.2 CB	7.4 AF	5.3 CB	7.8 AF	8.4 AF			
IX	Kapton	56065	6.12	1.8 AF		3.4 AP	0 AA	5.5 AF	5.11	0.2 CB	1.2 AF	1.8 AF	7.0 AF	8.4 AF	1.0 TF		
X	Hytrel	56065	3.0	7.3 AF			0 AA		7.0	0.6 AF	1.0 AF	6.0 TF	8.0 AF	9.0 AA	Decomposed		
XI	Kynar	DA552.1	5.5	1.1 AF			0.6 AA		7.0	1.8 AF	Debond	0.4 AF	Debond	0.2 AF	0		
XII	Kynar	80	5.0	2.9 CB		3.0 AP	4.5 CB	4.0 AP	1.5	2.8 AA	2.5 AA	4.6 AA	3.0 AA	3.8 AA	5.0 AA		
XIII	Delete																
XIV	3M8561	AB		3.5 AP			3.3 AP			1.6							
XV	3M5690	AB		3.0 AP			4.0 AP			2.6							
XVI	Kapton	Acrylic AB		5.5 AP			5.6 CB			4.7 AP	5.5 AF		5.8 CB	5.6 CB			
XVII	Kapton	Silicone AB		1.5 AP			2.0 AF			Debond	1.6 AF		2.0 AP	2.6 AP			
Coating																	
21	B274 Experimental	CAAPCO		2.0 TF			3.4 TF			0.2 AA	Failed	6.4 TF	10.0 TF	8.9 TF			
22	polyurethane	CAAPCO		4.0 TF			2.6 TF			1.0 AA	Failed	No start	2.7 TF	4.7 TF			
24	Fluoro-type II	CAAPCO		7.8 TF			7.5 TF			No start	Failed	10.2 TF	No start	9.0 TF	11.2 TF		
26	Astrialat Sterling			6.5 TF			0.4 AA			3.0 TF	Failed	4.3 TF	8.6 TF	5.3 TF	No start		
27	BMS 10-60	Desoto		No start			No start			No start	No start	No start	No start	No start	No start		
28	M313	Hughson		12.7 TF			1.5 TF			13.0 TF	Failed	14.0 AF	18.0 AF	19.0 TF	17.6 CB		
29	3400S	Dapcoat		0			0			0	-	Failed	0	-	0.2 CB		

* 1 lb/in = 1.752 N/cm

Note: Target peel strength = 17.5 N/cm (10 lb/in) width

AA = Adhesive/aluminum
 AP = Adhesive/primer
 AF = Adhesive/film
 CB = Cohesive bond
 AB = Adhesive backed
 RT = Room temperature
 TF = Tensile failure

Table C-6. Test Results—Visual Observations

[illegible]

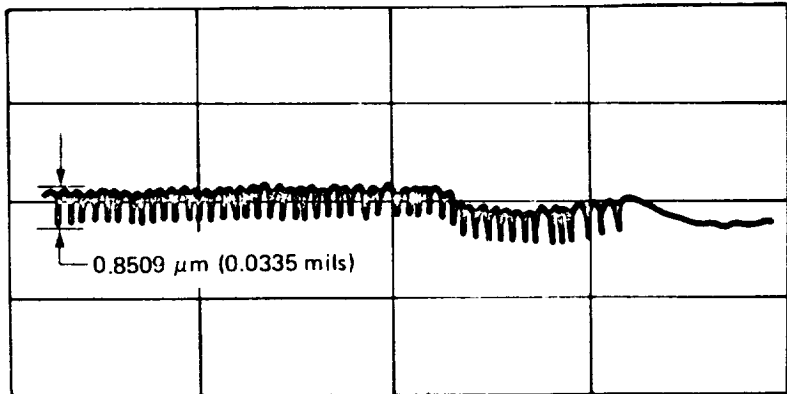
Notes: RT = Room temperature
F-10 = Failure on tenth day

Table C-7. Test Results—Pencil Hardness

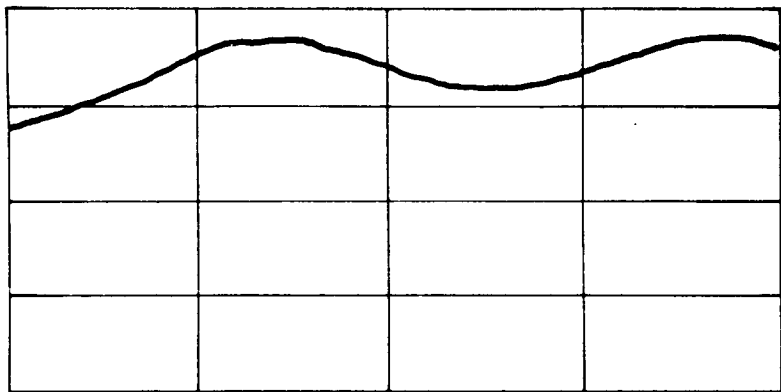
	Concept	Virgin	H ₂ O, RT, 1 day	Humidity, 49°C (120°F) 30 days	Jet fuel, RT 1 day	Hydraulic, RT, 7 days	Temper - ature, altitude	Dry heat, 239°C (460°F) 7 days
I	Kapton/PR1422	6H	6H	6H	6H	6H	6H	6H
II	Hytrel/PR1422	6H	6H	H	6H	3H	6H	6H
III	Tradlon/PR1422	6H	6H	6H	6H	6H	6H	6H
IV	Hytrel/DPAD6298	6H	6H	H	*	*	5H	6H
V	Tradlon/DPAD6298	6H	6H	6H	6H	6H	6H	6H
VI	Hituff/DPAD6298	H	HB	2B	*	*	H	H
VII	Hituff/7064	H	H	2B	3B	*	H	H
VIII	UHMW Polyolefin/AB	6H	6H	6H	6H	6H	6H	6H
IX	Kapton/56065	6H	6H	6H	6H	6H	6H	6H
X	Hytrel/56065	6H	6H	H	2H	2H	6H	6H
XI	Kynar/DA522-1	6H	2H	5H	6H	*	*	H
XII	Kynar/80	6H	3B	H	3B	6H	6H	6H
XIV	3M 8561/AB							
XV	3M 5690/AB							
XVI	Kapton/acrylic/AB	6H	6H	6H	6H	6H	6H	6H
XVII	Kapton/silicon/AB	3H	HB	3H	*	3H	3H	3H
21	Mil-C-83231 CAAPCO	6H	6H	6H	6H	*	6H	6H
22	Exp-polyurethane CAAPCO	6H	3H	6H	6H	*	6H	6H
24	Fluoro—type II CAAPCO	6H	6H	6H	HB	6H	6H	6H
26	Mil-C-83231 Sterling	6H	6H	6H	6H	*	6H	6H
27	BMS-10-60 Desoto	6H	6H	6H	6H	2H	6H	6H
28	M313 Hughson	6H	6H	6H	6H	*	6H	6H
29	Dapcoat 3400S	H	B	B	B	—	H	H

*Specimen failed during exposure

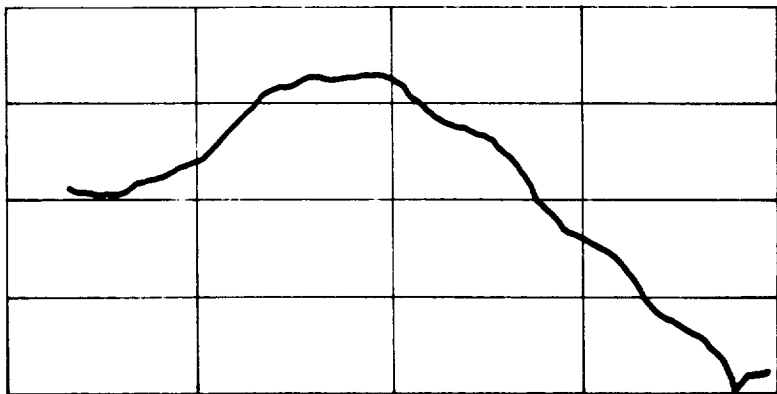
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Vertical scale:
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Calibration
standard
etched
glass



3M8561
film



3M5690
film

Figure C-1. Surface Smoothness Traces of Films

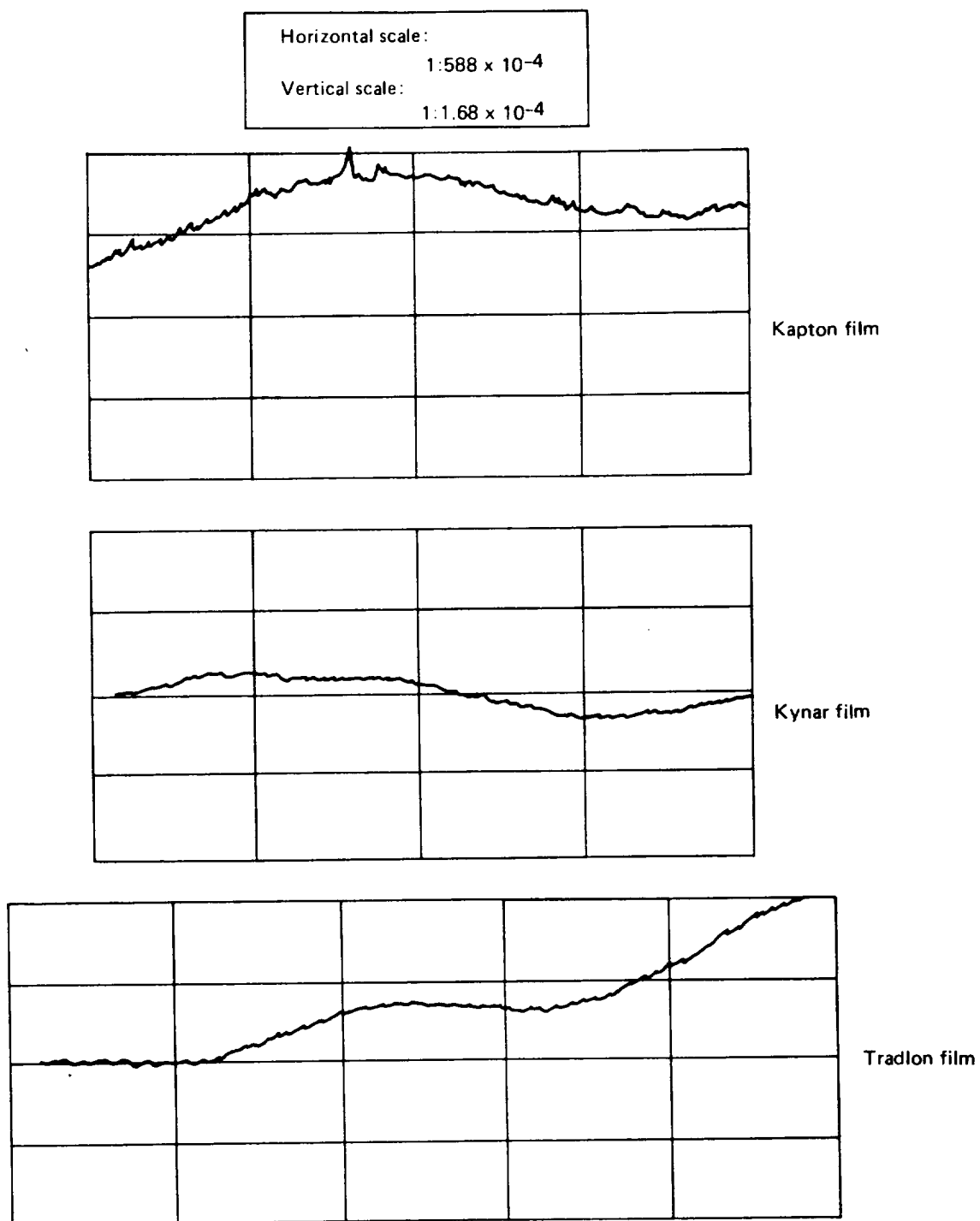


Figure C-1. Surface Smoothness Traces of Films (Cont)

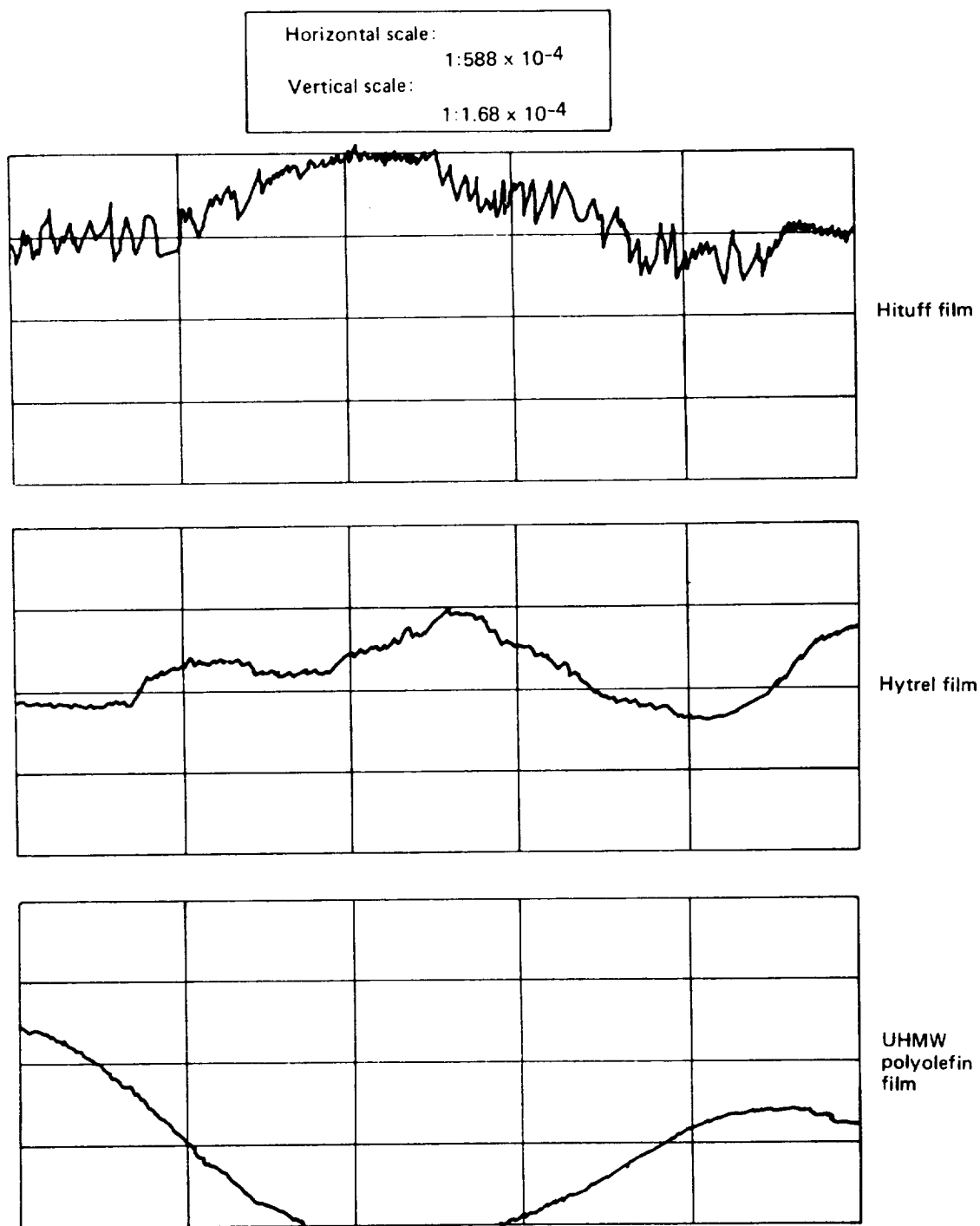


Figure C-1. Surface Smoothness Traces of Films (Cont)

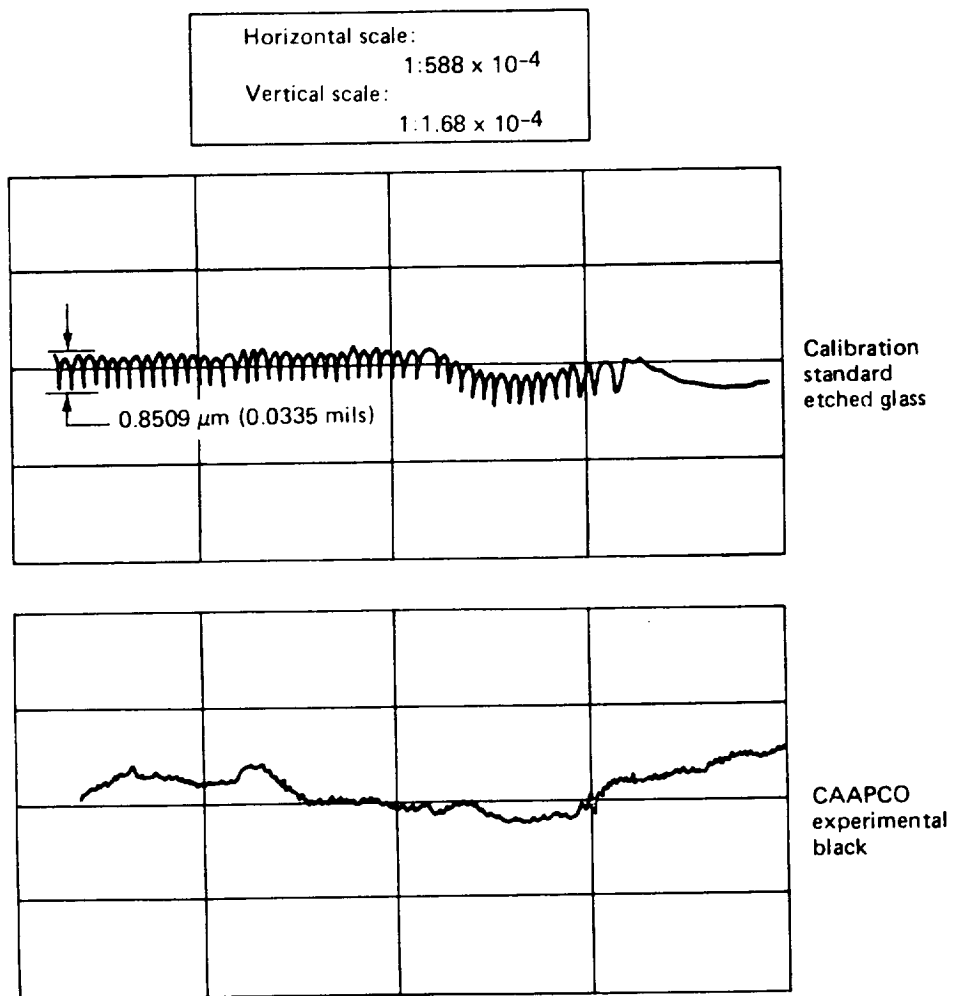
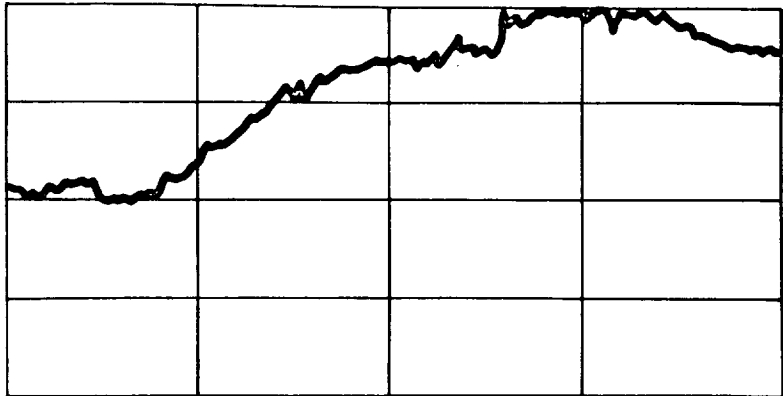
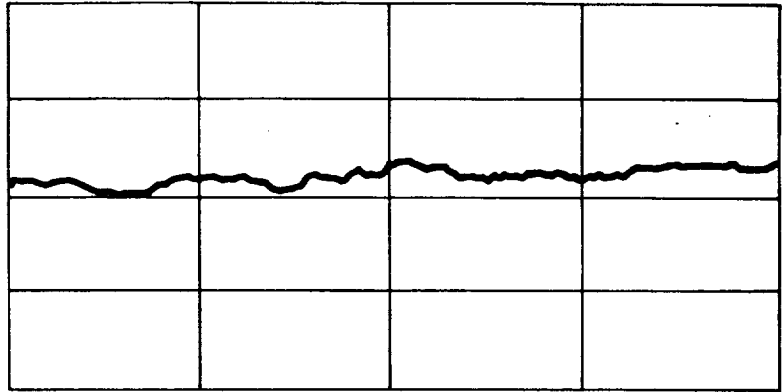


Figure C-2. Surface Smoothness Traces of Coatings

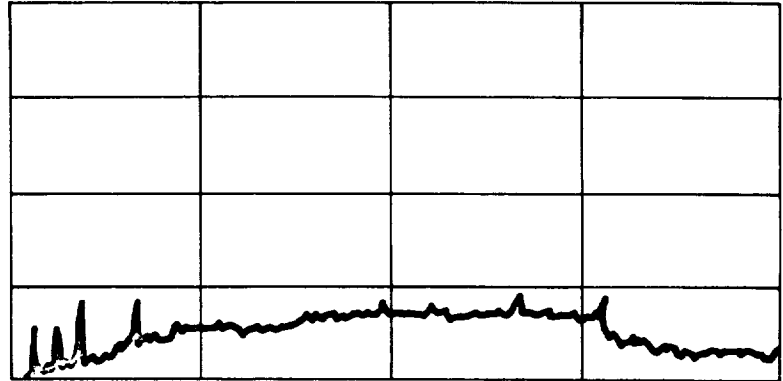
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Vertical scale:
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Sterling
astrocoat
MIL-C-83231



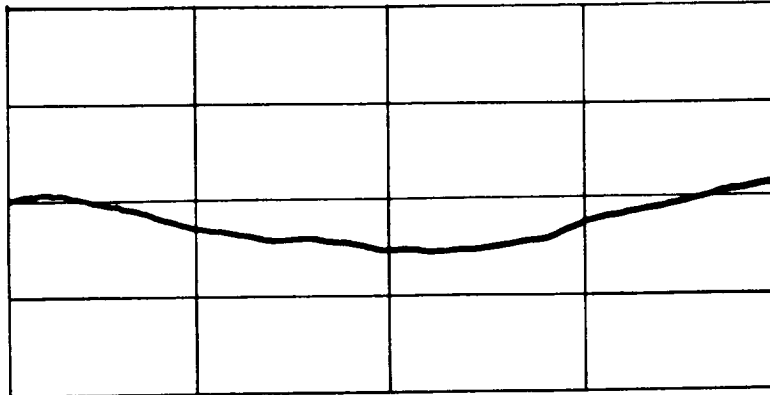
CAAPCO
B-274



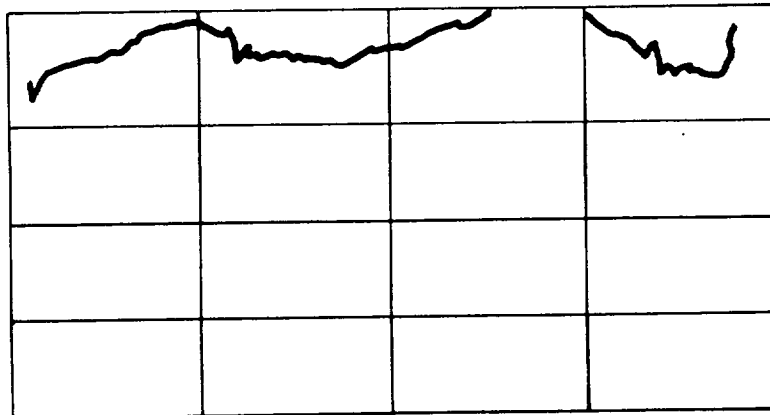
Hughson
M313

Figure C-2. Surface Smoothness Traces of Coatings (Cont)

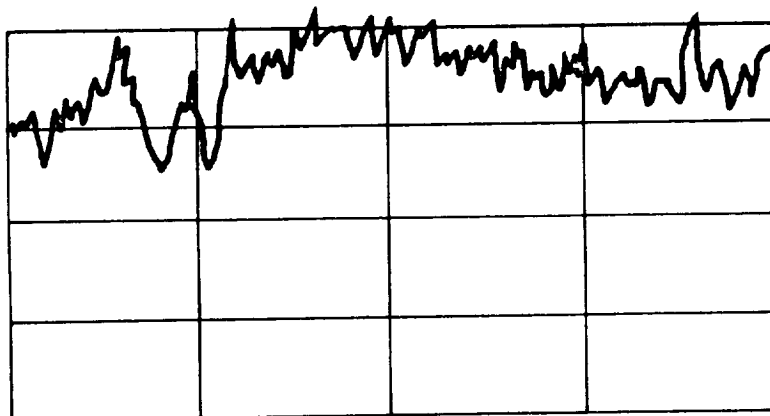
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Vertical scale:
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Desoto
BMS-10-60



CAAPCO
Type II
Fluoroelastomer



Dapcoat
3400S

Figure C-2. Surface Smoothness Traces of Coatings (Cont)

APPENDIX D

APPLICATION METHOD DESCRIPTION

Aluminum Surface Preparation—Alclad Surface

Clean with Scotchbrite and an alkaline cleaner such as Alkanox. Alodine the cleaned surface. Apply 0.013 mm (0.5 mil) to 0.025 mm (1.0 mil) of primer. MIL-P-23377 primer or BMS 10-79 primer are both satisfactory.

Spray Application of Liquid Coatings

1. Sterling Astrocoat MIL-C-83231

This catalyst-activated, moisture-curing polyurethane coating requires approximately 12 applications at 1 hr intervals to achieve 0.254 to 0.305 mm (10 to 12 mils) of coating. Control of humidity and temperature is an absolute necessity for proper application. A minimum of 50% relative humidity at 21°C (70°F) is needed for between-coat cure. Severe bubbling will occur if each coat is not cured before the next coat is applied. Force curing at high humidity (70%) between coats is acceptable; time interval between coats can be cut to 45 min. Postcuring of 3 to 7 days is recommended. A wash primer is included in each kit. The Astrocoat coating is, however, compatible with epoxy-type primers. Coating tends to have an "orange peel" appearance. Surface blemishes (dust and lint bumps) are normal and unavoidable. Coating application, difficult and tedious, requires master-level painter. Priming 8 to 16 hr before coating application is recommended. The spray application must be performed with adequate ventilation as flammable solvents are contained in the coating system.

2. Hughson M313 Black Chemglaze

A two-component, nonmoisture-curing polyurethane coating. It requires 3 to 5 applications at 1- to 2-hr intervals to achieve 0.254 to 0.305 mm (10 to 12 mils) of coating. Control of humidity is not required but application at temperatures less than 21°C (70°F) is not recommended. Activated vehicle has a 2-hr pot life. Only a sufficient vehicle for each application should be activated at any time. Curing agent is sensitive to moisture. Several crosscoats are applied and allowed to cure for 1 to 2 hr before the next series of crosscoats are applied. Coating must be applied to a primed (epoxy or polyvinylbutyral) surface. Minimal experience is required to apply coating. Post curing of 3 to 5 days is recommended; coating can be heat-cured to shorten postcure period. The spray process must be performed with adequate ventilation.

3. CAAPCO B-274

A two-component, nonmoisture curing, nonyellowing polyurethane coating. It requires 9 to 12 coats at 10 to 30 min intervals to achieve 0.254 to 0.356 mm (10 to 14 mils) of coating. Application at temperatures less than 21°C (70°F) is not recommended. Pot life of the activated vehicle is greater than 4 hr. Coating is applied to primed surfaces. MIL-P-23377 epoxy or MIL-P-15328 wash primers are recommended. Priming 30 to 60 min before coating application is recommended.

Post curing of 2 to 3 days is recommended; postcure can be accelerated by heat. Minimal experience is required to apply coating. No special facilities are required for application. As with the two previous coatings, there must be adequate ventilation used in the spraying of this material.

Bonding Application of Free Film Materials

Adhesive is applied by brush or spraying to desired thickness. The plastic film is then “wallpapered” onto the prepared wing. While tension is applied to the ends of the plastic sheet, the film is smoothed with a squeegee. After the surface is smoothed, the part is allowed to cure.

APPENDIX E

P-STATIC NOISE TESTING OF SURFACE COATING MATERIALS

Summary

Triboelectric environments were simulated by generating electrical charges on the surface coating material of each test specimen as shown in figure E-1. Each test specimen was a bare aluminum sheet 46 x 46 cm (18 x 18 in) and 2.73 mm (0.068 in) thick, with a coating material applied to one side. The eight specimens tested are described in table E-1.

Megohmmeter resistance measurements are recorded in table E-2, and P-static noise results are recorded in table E-3. Figure E-2 shows oscilloscope traces of streamer effects for Tradlon/ PR 1422 film/adhesive and CAAPCO B-274 liquid coating. These characteristics are typical for the films and coatings tested.

Table E-3 shows that test specimens 2, 3, and 4 (CAAPCO B-274, Astrocoat and Chemglaze M313) are unquestionably the least susceptible to P-static noise generation under laboratory conditions.

Discussion

In the surface charging tests the total dc current was closely controlled to 30 μ A. The total dc supply current equalled approximately the "through" plus the ring currents ($I_t = I_1 + I_2$), therefore, the stray current losses were kept to a minimum. Thus, no high intensity arcing/streamer noises interfered with the desired test results of P-static noise measurements.

P-static noise indicators are: (a) high surface charge voltage of the test specimen; and (b) surface streamer effects. Observed audible noises, arcing, erratic dischargings, and surface charges left after the high-voltage power supply was turned off were noted. This information is recorded in table E-3 for each test specimen. Tested specimens 2, 3, and 4 showed very little measured surface charge voltage and none of the other P-static noise symptoms. Specimen 1, a possible borderline case, developed a large surface charge voltage and slight surface streamer when tested.

Conclusion

Specimens 2, 3, and 4 are the least susceptible to P-static noise generation in a triboelectric environment. Specimen 1 was borderline and therefore must either be excluded or evaluated further. Specimens 5, 6, 7 and 8 are considered to be potential P-static noise and spark sources.

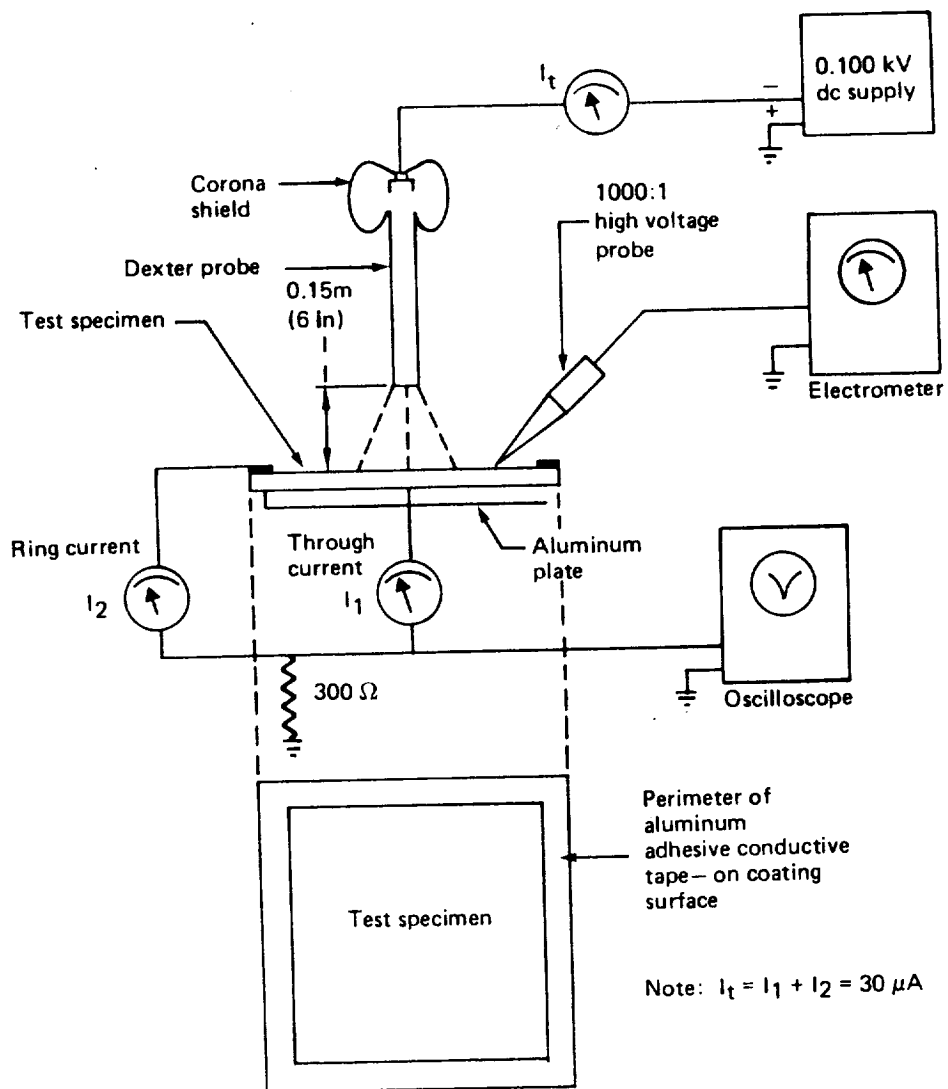


Figure E-1. P-Static Test Setup

Table E-1. Condition of P-Static Test Panels as Received*

Test specimen number	Specifications	Concept	Surface appearance
1	CAAPCO B-274 + ASP108	21 + AS	Black, tacky finish, with oil film marks
2	CAAPCO B-274	21	Same appearance as 1, except cleaner; superficial surface dents
3	Astrocoat	26	Black, tacky dust particles, orange peel glossy surface, packing material residue
4	Chemglaze	28	Same as 3 with mottled pattern
5	Kapton/PR1422 polysulfide	I	Hard dark reddish-brown semigloss surface; eight strings of dents serially together, single dents at middle and elsewhere
6	Tradlon/PR1422 polysulfide	III	Hard dark reddish-brown mirror; uneven surface yellow streak and joint in coating running across surface from edge to edge, faintly visible in the middle
7	UHMW polyolefin adhesive back	VIII	Soapy, dull, streaky yellowish green surface finish. Also many blister spots cover 1/3 the panel surface area.
8	Kynar/adhesive 80	XII	Same as 7, except no streaks

*Condition observed by contractor test personnel upon receipt of panels from subcontractor. Preparation of panels by the subcontractor was expedited to meet P-static test schedules. A high-quality surface condition was not a requirement for these tests.

Table E-2. Resistance Measurement

Test specimen number	Megometer readings (megs)				Comments
	Applied 50V		Applied 500V		
	Surface resistance	Through resistance	Surface resistance	Through resistance	
1	2×10^3	5×10^3	3×10^2	2.5×10^2	Resistances increase steadily to the constant value in 40 to 60 sec.
2	2×10^4	∞	1.5×10^4	0.8×10^5	
3	2×10^4	5×10^4	10^4	1.4×10^4	
4	2.2×10^4	10^5	2×10^4	4×10^4	
5	10^5	∞	10^5	1.6×10^5	
6	8×10^4	∞	8×10^4	2.6×10^5	
7	2×10^5	∞	2×10^5	10^5	
8	3×10^4	∞	2.2×10^4	2×10^5	

Table E-3. P-Static Noise Test Data

Test specimen number	Power supply voltage kV	Power supply current, μ A	Ring current, μ A	Through current, μ A	Charge voltage on surface, kV	Pulse streamer present	Test description *
Calibration sample	50.0	30.0	30.0	1.0	-14.0 to 15.0	Yes, see figure E-2	1, 2, 3, 4
1	52.2	30.0	11.0	19.0	-11.2	Slight	None of these
2	60.0	30.0	0	32.0	+0.030	No	None of these
3	63.5	30.0	0	32.0	+0.020	No	None of these
4	58.8	30.0	0	32.0	+0.180	No	None of these
5	62.8	30.0	8.0	21.0	-8.60	Yes	Heavy 4
6	57.9	31.0	0.5	27.0	-6.8 to -7.0	Yes	Distinct 2 and very heavy 4
7	68.8	30.0	0	30.0	-7.7 to -8.0	Yes	Heavy 4
8	56.3	30.0	1.0	31.0	-3.8 to -4.0	Yes	Slight 4

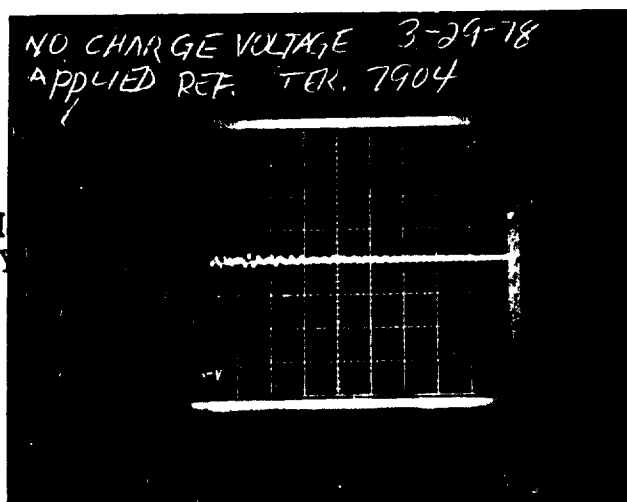
*1 = Audible noise present

2 = Arcing

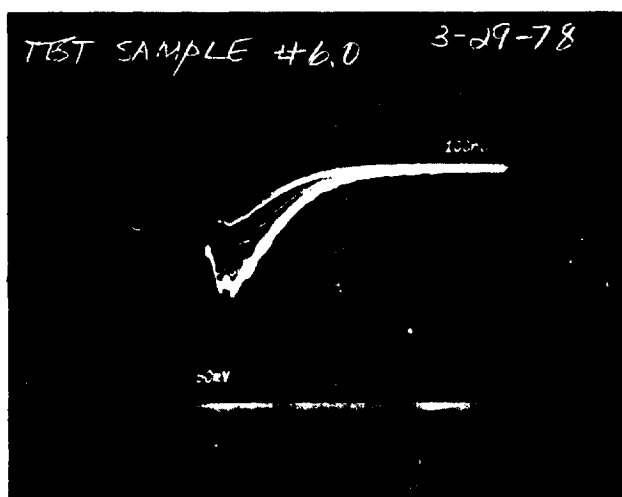
3 = Erratic discharges

4 = Surface charge left with power supply off

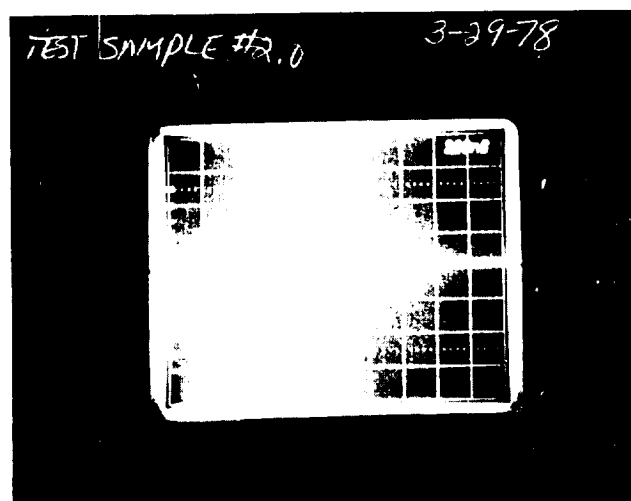
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Ambient noise reference level



Noise pulses—Tradlon film/PR1422 adhesive



Noise pulses—CAAPCO B-274

Figure E-2. P-Static Noise Comparison

1. Report No. CR-158954	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Aircraft Surface Coatings Study		5. Report Date January 1979	
		6. Performing Organization Code	
7. Author(s) BCAC Preliminary Design Department		8. Performing Organization Report No. D6-46699	
		10. Work Unit No.	
9. Performing Organization Name and Address Boeing Commercial Airplane Company (BCAC) P.O. Box 3707 Seattle, Washington 98124		11. Contract or Grant No. NAS1-14742	
		13. Type of Report and Period Covered Contractor Report - Final	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code	
15. Supplementary Notes This report covers work conducted under one of five tasks included in Contract NAS1-14742.			
16. Abstract Surface coating materials, for application on transport-type aircraft to reduce drag, were investigated. The investigation included two basic types of materials: spray-on coatings and adhesively bonded films. A cost/benefits analysis was performed, and recommendations were made for future work toward the application of this technology.			
17. Key Words (Suggested by Author(s)) Drag reduction Films Erosion protection Energy efficiency Coatings			
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages	22. Price*

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